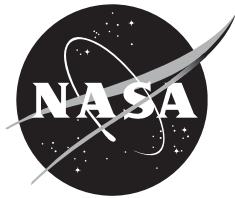


NASA/CR-2011-215986



# **Center-TRACON Automation System (CTAS) En-route Trajectory Predictor Requirements and Capabilities**

*Vivona, Robert A.  
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*NASA Ames Research Center, California*

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**April 2013**

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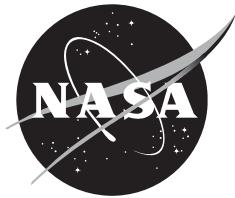
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# **Center-TRACON Automation System (CTAS) En-route Trajectory Predictor**

## **Requirements and Capabilities**

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## **1. INTRODUCTION**

This requirements framework document is designed to support the capture of requirements and capabilities for state-of-the-art trajectory predictors (TPs). This framework has been developed to assist TP experts in capturing a clear, consistent, and cross-comparable set of requirements and capabilities. The goal is to capture capabilities (types of trajectories that can be built), functional requirements (including inputs and outputs), non-functional requirements (including prediction accuracy and computational performance), approaches for constraint relaxation, and input uncertainties.

The sections of this framework are based on the Common Trajectory Predictor structure developed by the FAA/Eurocontrol Cooperative R&D Action Plan 16 Committee on Common Trajectory Prediction. It is assumed that the reader is familiar with the Common TP Structure.<sup>1</sup>

This initial draft is intended as a first cut capture of the En Route TS Capabilities and Requirements. As such, it contains many annotations indicating possible logic errors in the CTAS code or in the description provided. It is intended to work out the details of the annotations with NASA and to update this document at a later time.

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<sup>1</sup> FAA/Eurocontrol Cooperative R&D Action Plan 16: Common Trajectory Prediction Capability (2004), *Common Trajectory prediction-Related terminology, Version 2.0*.

## 2. TRAJECTORY PREDICTOR DESCRIPTION

### 2.1. Overview

The CTAS En Route TP is the engine that drives the en route Decision Support Tools (DSTs) within NASA Ames' Center-TRACON Automation System (CTAS). CTAS is a suite of tools that provide advisories to air traffic controllers and managers to help them manage increasingly complex traffic flows. The en route CTAS tools, including the Traffic Management Advisor (TMA), En Route Descent Advisor (EDA) and Direct-To (D2) provide a variety of services to controllers and traffic managers. These services, which are all built upon aircraft trajectory prediction, include:

- time-based scheduling
- conflict probe (predicted loss of separation detection)
- trial ("what if") lateral and vertical path planning
- conflict resolution lateral and vertical path advisories, including conflict free metering conformance
- meet-time lateral and vertical path advisories
- descent management advisories (efficient top-of-descent initiation)

CTAS works with other en route systems within its adapted Air Route Traffic Control Center (ARTCC), including the ARTCC's Host computer, to provide its services for a range of aircraft flight plan categories. These flight plan categories are described in Table 2.1-1

Aircraft Flight Plan Category	Description
Satellite	An aircraft that departs from a Satellite airport within the adapted ARTCC and arrives at a Satellite airport in the adapted ARTCC.
Satellite Departure	An aircraft that departs from an airport within the adapted TRACON and arrives at a Satellite airport in the adapted ARTCC.
Satellite to External	An aircraft that departs from a Satellite airport within the adapted ARTCC and exits into an adjacent ARTCC.
External to Satellite	An aircraft that enters the ARTCC from an adjacent ARTCC and arrives at a Satellite airport within the adapted ARTCC.
Departure	An aircraft that departs from an airport within the adapted TRACON and exits into an adjacent ARTCC.
Overflight	An aircraft that enters the ARTCC from an adjacent ARTCC and exits into an adjacent ARTCC.
Satellite Arrival	An aircraft that departs from a Satellite airport within the adapted ARTCC and arrives at an airport in the adapted

	TRACON.
Departure Arrival	An aircraft that departs from an airport within the adapted TRACON and arrives at an airport within the adapted TRACON (must enter the ARTCC airspace).
Arrival	An aircraft that enters the ARTCC from an adjacent ARTCC and arrives at an airport within the adapted TRACON.

**Table 2.1-1: Aircraft Categories Supported by CTAS and the CTAS En Route TP**

As a baseline for its scheduling services, CTAS requests “direct to meter fix” lateral path estimations from the CTAS En Route TP for its Arrival aircraft. For conflict probe and most other services, CTAS requests flight-plan- or controller-input-based lateral path estimations.

CTAS can request either full trajectories or, for Arrival aircraft, just times at the metering fix. When asking for just times, the times from trajectories for a range of pilot procedures can be requested:

- FAST procedure = uses the maximum appropriate speeds for the aircraft
- SLOW procedure = uses the slowest appropriate speeds for the aircraft
- NOMINAL procedure = uses typical speeds for the aircraft

The definition of the specific choice of speeds for each of these procedures is described in the document.

It should be noted that CTAS does not make a distinction between the aircraft’s indicated airspeed (IAS) and its calibrated airspeed (CAS). The use of CAS in the document is assumed equivalent to the use of IAS.

## **2.2. Trajectory Prediction Triggers**

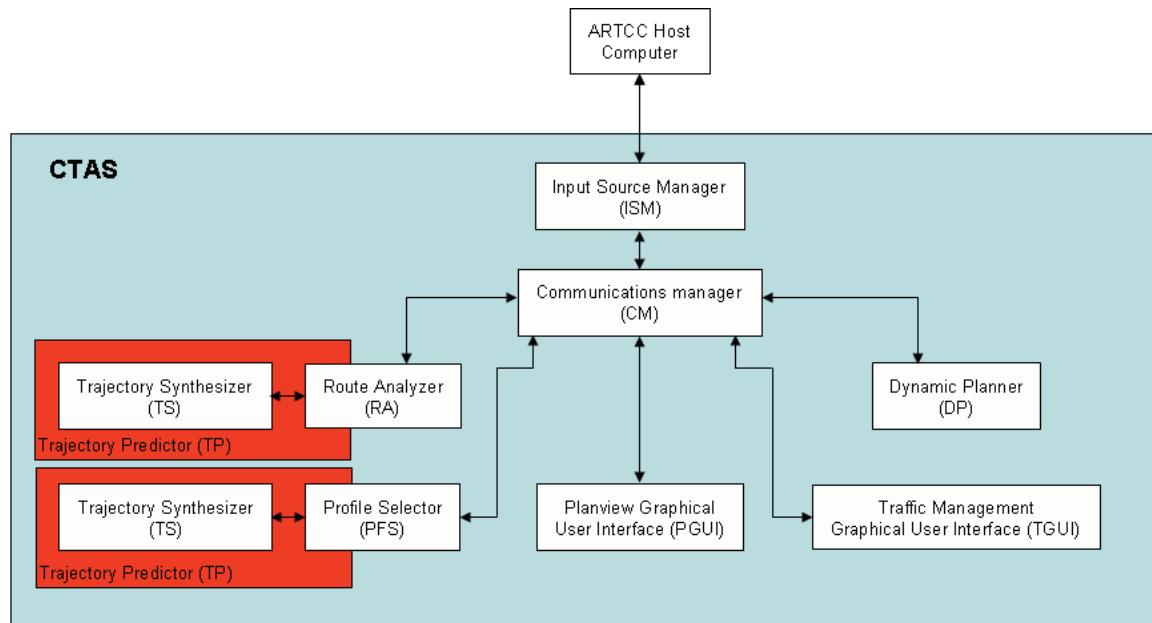
The CTAS En Route TP is requested to return a trajectory prediction under one of the following events:

- Receipt of the First Flight Plan – An aircraft’s flight plan is received by the ARTCC before radar track, so the first indication of a new aircraft is the receipt of its flight plan. This first flight plan initiates a trajectory prediction request. In this instance, the aircraft is considered non-active (see Section 3.1.1).
- Receipt of a Flight Plan Amendment – Whether active or non-active, the receipt of a flight plan amendment causes a new trajectory to be generated.
- Receipt of Track Data – An aircraft that has received radar tracks is an active aircraft. Each radar track received causes a new trajectory request.
- Trial Plan Request – Receipt of CTAS trial plan information causes an immediate request for a trajectory.
- Gate Balance Meter Fix Change – For Traffic Flow Management (TFM) applications, CTAS can request a meter fix change for an Arrival aircraft. This change causes a request for a new trajectory.

### **2.3. TP Architecture and Client Application Interfaces**

Figure 2.3-1 illustrates the software architecture of CTAS. CTAS combines several independent processes (ISM, CM, RA, etc.) to create an instance of a Decision Support Tool (DST). Examples include TMA (instantiated by ISM, CM, DP, TGUI, and multiple RA/TS), and EDA (instantiated by ISM, CM, PFS/TS, and multiple RA/TS).

The CTAS En Route Trajectory Predictor is comprised of the Trajectory Synthesizer (TS) process, as well as parts of the Route Analyzer (RA) and Profile Selector (PFS) processes. Within CTAS, the TS is responsible for some of the Preparation Processing, all of the Trajectory Engine Processing, as well as most of the Trajectory Update and Trajectory Export Processing. The RA and PFS mainly provide elements of the Preparation Processing.



**Figure 2.3-1 CTAS Software Architecture**

### 3. TP INPUT DATA

#### 3.1. State and Intent data

##### 3.1.1. State

Table 3.1.1-1 describes the aircraft state information input to the CTAS En Route TP.

	Input	Description
Aircraft Type		<b>FAA 4-character aircraft type</b>
X/Y		<b>Aircraft initial position</b>
Altitude		<b>Aircraft initial condition altitude</b>
Time		<b>Aircraft initial condition time</b>
Speed		<b>Aircraft initial condition true airspeed or ground speed</b>
Course		<b>Aircraft initial condition true course</b>
Vertical Speed		<b>Aircraft initial condition vertical speed</b>

**Table 3.1.1 – 1 CTAS En Route TP State Inputs**

The X/Y coordinate frame used by the ARTCC Host computer is presented in Appendix A.

There are two surveillance categories for aircraft identified by CTAS:

1. **Active**: Aircraft that are currently under radar surveillance.
2. **Non-Active**: Aircraft that are not currently under radar surveillance, so only intent information for that aircraft is available.

The aircraft state (initial condition) processing for the CTAS TP varies based on these two categories. Table 3.1.1-2 defines the sources of the initial state data for active aircraft.

	Input	Source
Aircraft type		<b>Host flight plan aircraft type</b>
X/Y		<b>From radar track</b>
Altitude		<b>Altimeter (Pressure) altitude from aircraft transponder</b>
Time		<b>From radar track</b>
Speed		<b>Ground speed from radar track</b>
Course		<b>From radar track filtering (see Appendix B)</b>
Vertical Speed		<b>From radar track filtering (see Appendix B)</b>

**Table 3.1.1 – 2 Source of Active Aircraft State Inputs**

The CTAS En Route TP can filter (if configured to do so) radar track ground speed, vertical speed, and course. This processing is described in Appendix B.

Table 3.1.1-3 defines the sources of the initial state data for Arrival, Overflight, and External to Satellite non-active aircraft.

Input	Source
Aircraft type	<b>Host flight plan aircraft type</b>
X/Y	<b>Host flight plan coordination fix position</b>
Altitude	<b>Host flight plan filed altitude</b>
Time	<b>Host flight plan coordination time</b>
Speed	<b>Host flight plan filed airspeed.</b> This is a true airspeed that is converted by the CTAS En Route TP based on the aircraft atmospheric model.
Course	<b>The course is set as the true course from the x/y location to the first waypoint in the flight plan route</b>
Vertical Speed	<b>Defaulted to 0.0</b>

**Table 3.1.1 – 3 Source of Arrival, Overflight, and External to Satellite Non-Active Aircraft State Inputs**

Table 3.1.1-4 defines the sources of the initial state data for Departure, Departure Arrival, Satellite, Satellite Arrival, Satellite Departure, and Satellite to External non-active aircraft.

Input	Source
Aircraft type	<b>Host flight plan aircraft type</b>
X/Y	<b>Airport location or Flight Plan Coordination Fix (if different from airport)</b>
Altitude <sup>2</sup>	<b>Airport Elevation (if coordination fix at airport) or Flight Plan Altitude (if coordination fix different from airport)</b>
Time	<b>Host flight plan coordination time</b>
Speed	<b>Host flight plan filed airspeed.</b> This is a true airspeed that is converted by the CTAS En Route TP based on the aircraft atmospheric model.
Course	<b>The true course calculated from x/y to the start of the flight plan route.</b>
Vertical Speed	<b>Defaulted to 0.0</b>

**Table 3.1.1 – 4 Source of Departure, Departure Arrival, Satellite, Satellite Arrival, Satellite Departure, and Satellite to External Non-Active Aircraft State Inputs**

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<sup>2</sup> If the airport elevation is not known, the CTAS adapted airport elevation is used. Also, if the airport is not known, the filed altitude is used. These are not “intent modeling” but protections used by a research system that would not occur in an operational system, so was not added to intent modeling.

### 3.1.2. Intent

Table 3.1.2-1 describes the aircraft intent information input to the CTAS En Route TP.

Input	Description	Source
<b>Flight Plan Route String</b>	<i>Flight Plan Data</i> The field 10 data from the aircraft's FAA flight plan	<b>Host Flight Plan</b>
<b>Host AK Data</b>	A list of route waypoints generated by the Host Computer by parsing the Flight Plan Route String	<b>Host Computer Output</b>
<b>Filed Cruise Altitude</b>	Aircraft's current cruise altitude	<b>Host Flight Plan</b>
<b>Filed Cruise Speed</b>	Filed true airspeed <i>User Defined Route Data</i>	<b>Host Flight Plan</b>
<b>Capture Waypoint</b>	Waypoint at which to transition back to the flight plan route.	<b>User Input</b>
<b>Auxiliary Waypoint(s)</b>	One or more user-defined waypoints to follow prior to the Capture Waypoint.	<b>User Input</b>
<b>Turn Out Course</b>	Capture course for initial turn out before proceeding to a Capture Waypoint	<b>User Input</b>
<b>Waypoint Capture Delay Time</b>	Delay time before initiating the turn back to capture a Capture Waypoint. <i>Reference Data</i>	<b>User Input</b>
<b>Reference Waypoint Position and Elevation</b>	Used to translate arbitrary airspace locations (e.g., TOD location) into identifiable locations using fix-radial-distances (slant range).	<b>User input</b>
<b>Altimeter Setting</b>	Used to translate transponder altitude readings into geometric altitudes below FL180. <i>User Constraints</i>	<b>User Input</b>
<b>Cruise Speed Constraint</b>	Mach or CAS cruise speed constraint	<b>User Input</b>
<b>New Cruise Altitude</b>	A desired change in the aircraft's current cruise altitude.	<b>User Input</b>
<b>Descent Mach Constraint</b>	Speed constraint for constant Mach portion of the aircraft's descent profile	<b>User Input</b>
<b>Descent CAS Constraint</b>	Speed constraint for constant CAS portion of	<b>User Input</b>

<b>Descent Weight</b>	the aircraft's descent profile Override of default aircraft model typical descent weight	User Input
<b>Crossing Altitude Restriction</b>	Changes the default (letters of agreement) altitude constraint at the metering fix.	User Input
<b>Crossing Speed Restriction</b>	Changes the default (letters of agreement) speed constraint (CAS) at the metering fix.	User Input
<b>Climb Mach Constraint</b>	Speed constraint for constant Mach portion of the aircraft's climb profile	User Input
<b>Climb CAS Constraint</b>	Speed constraint for constant CAS portion of the aircraft's climb profile	User Input
<b>Waypoint Capture</b>	<i>TP Modes</i> Lateral Path Mode that uses auxiliary waypoints, a capture waypoint, and the flight plan route to determine the aircraft's lateral path.	User Input
<b>Path Stretch</b>	Lateral Path Mode that uses a turnout course, a capture waypoint delay time, a capture waypoint, and the flight plan route to determine the aircraft's lateral path.	User Input
<b>Priority</b>	Lateral Path Mode that sends an aircraft direct to the airport.	User input.

**Table 3.1.2 – 1 CTAS En Route TP Intent Inputs**

### **3.2. State/Intent Modeling Processing Controls**

Table 3.2-1 describes the state and intent processing control inputs to the CTAS En Route TP. See Section 4.1.3 (Intent Modeling) for processing details related to these inputs.

Input	Description
<b>Speed Limiter Mode</b>	Causes internal intent modeling to replace certain input speeds (primarily initial condition speeds) with aircraft model limits, if appropriate.
<b>No Initial Track Received</b>	Identifies when an initial condition must

<b>Observed Turn Radius</b>	be estimated due to a lack of a surveillance track record.
<b>Override Initial Condition CAS</b>	Used to override the normal turn modeling for a turn at the aircraft's initial condition. The input turn radius is based on observations of previous aircraft states.
<b>Adaptive Thrust Modeling</b>	Used to replace the initial condition CAS with the aircraft model's default Climb CAS.
<b>Cruise Speed Mode</b>	Activates adaptive thrust modeling in aircraft performance model (see Section 4.2.4.3)
<b>Descent Speed Mode</b>	Used to identify which speed values from the aircraft model to use during intent modeling to determine the Cruise Mach and CAS. Values include: Maximum Value, Minimum Value, Minimum Cruise or Descent CAS, Input Value, and Minimum Cruise Value or Input Value. Used to identify which speed values from the aircraft model to use during intent modeling to determine the Descent Mach and CAS. Values include: Maximum Value, Minimum Value, Input Value, Minimum Cruise Equals Descent Value, Nominal Value and Sub Nominal Value (including input percentage).

Table 3.2 – 1 CTAS En Route TP State/Intent Processing Control Inputs

### **3.3. Adaptation Data**

Adaptation data used by the CTAS En Route TP comes from the adaptation data used by the adapted ARTCC's Host computer. Table 3.3-1 describes the adaptation data used by the CTAS En Route TP.

Name	Use	Data Description
<b>A-Line Definitions</b>	Used for flight plan route parsing. Specifically to relate a flight plan route with a Preferred Arrival Route.	Defines a-line geometry, including altitude and aircraft class restrictions and relates to an associated PAR.
<b>Aircraft Characteristics</b>	Used to relate FAA 4-character aircraft type to class of aircraft (J, K, L, etc.)	Provides Average Climb Rate, Adapted Descent Rate, Adapted Climb Rate and Aircraft Class Type as a function of aircraft type.

<b>Airports</b>	<b>Defines the location and elevation of airports within the adapted ARTCC.</b>	<b>Provides airport latitude, longitude and elevation.</b>
<b>Jet Airways/Victor Airways/Coded Routes</b>	<b>Defines the fixes along a published airway/route.</b>	<b>Provides an ordered list of fixes for each airway/route.</b>
<b>Departure Fixes</b>	<b>For each departure gate, defines the crossing restrictions at the departure fixes.</b>	<b>For each departure fix within a departure gate, provides the altitude and airspeed restriction as a function of aircraft type (Jet, Turboprop, Prop) and departure runway.</b>
<b>Satellite Arrival Fixes</b>	<b>Used to define arrival fixes for satellite airports.</b>	<b>For each airport, provides arrival fix names for specified routes into that airport.</b>
<b>Arrival Fixes</b>	<b>Used to define arrival (meter) fixes for arrival aircraft.</b>	<b>For each arrival gate, provides the arrival fixes and outer meter fixes, including crossing altitude/speed restrictions as a function of aircraft class (Jet, etc.) and runway assignment.</b>
<b>Preferred Arrival Routes (PARs)</b>	<b>Used during flight plan parsing when aircraft is following a PAR.</b>	<b>For each airport, defines the altitude range and fixes associated with a PAR. Also defines the flight plan field 10 definition of that PAR.</b>
<b>Preferred Departure/Arrival Routes (PDARs)</b>	<b>Used during flight plan parsing when aircraft is following a PDAR.</b>	<b>For each airport, defines the altitude range and fixes associated with a PDAR. Also defines the flight plan field 10 definition of that PDAR.</b>
<b>Preferred Departure Routes (PDRs)</b>	<b>Used during flight plan parsing when aircraft is following a PDR.</b>	<b>For each airport, defines the altitude range and fixes associated with a PDR. Also defines the flight plan field 10 definition of that PDR.</b>
<b>Standard Instrument Departures (SIDs)</b>	<b>Used during flight plan parsing when aircraft is following a SID.</b>	<b>For each airport, defines the altitude range and fixes associated with a SID. Also defines the flight plan field 10 definition of that SID.</b>
<b>Standard Arrival Routes</b>	<b>Used during flight plan</b>	<b>For each airport, defines</b>

(STARs)	parsing when aircraft is following a STAR.	the altitude range and fixes associated with a STAR. Also defines the flight plan field 10 definition of that STAR.
Waypoints	Used to define the position of fixes used in other definitions (routes, airways, SIDs, STARs, etc.)	Provides the latitude and longitude of published and Host adapted waypoints.

**Table 3.3 – 1 CTAS En Route TP Adaptation Data**

### **3.4. Meteorological (Atmospheric) Data**

Table 3.4-1 describes the types of en route atmospheric data that the CTAS En Route TP can accept as inputs.

Weather Data Type	Description	Source
RUC 211	Uses the AWIPS 211 grid to generate an 80 kilometer binary grid.	Live connection to RUC weather provider.
RUC 236	Uses the AWIPS 236 grid to generate a 40 kilometer binary grid.	Live connection to RUC weather provider.
RUC 252	Uses the AWIPS 252 grid to generate a 20 kilometer binary grid.	Live connection to RUC weather provider.
Standard Atmosphere	Uses standard atmosphere equations (or grid data).	Internal

**Table 3.4-1: CTAS En Route TP Meteorological Data Model Types**

Currently, the RUC 211 grid is used for release builds of CTAS, but RUC 236 grid is becoming the baseline standard. The RUC 252 model is being explored as a replacement for both of these grids.

The standard atmosphere is only used in non-live situations (i.e., simulations) or as noted in the descriptions below.

## 4. TP CAPABILITIES & FUNCTIONAL REQUIREMENTS

### 4.1. Preparation Process

#### 4.1.1. Lateral Path Constraint Identification

##### 4.1.1.1. Flight Plan Route Parsing

There are two modes of flight plan parsing available to the CTAS En Route TP: (1) using internal CTAS route parsing, or (2) using a combination of Host AK route data and internal CTAS route parsing. The choice of flight plan parsing method is a runtime option for CTAS.

When using internal CTAS route parsing, the decomposition of the flight plan's field 10 route of flight into a list of waypoints is performed by CTAS. CTAS has the ability to translate (using its adaptation database) the following types of route elements into a list of waypoints:

- Airports (Origin and Destination)
- Waypoint Names
- Lat/Lon Locations<sup>3</sup>
- Fix-Radial-Distance (FRD) Locations<sup>5</sup>
- Airways (Jet and Victor)
- Special Airways
- Coded Routes
- Preferred Departure Routes (PDR)
- Preferred Departure Arrival Routes (PDAR)
- Preferred Arrival Routes (PAR)
- Standard Instrument Departures (SID)
- Standard Arrival Routes (STAR)

Host AK Route data is comprised of a list of waypoints that result from the Host Computer's parsing of the flight plan route. As such, it only contains data for the part of the flight plan route that is within the ARTCC boundaries. If the aircraft is not terminating the en route portion of its flight within the ARTCC airspace, the internal CTAS route parsing (described above) is used to parse the en route portion of the route that is outside the ARTCC and this is connected to the AK route data to create a completely parsed route. Host AK route parsing requires the same ability to convert Lat/Lon and Fix-Radial-Distance (FRD) Locations as used in the internal CTAS route parsing.

Once parsed into a list of waypoints (by either of the two methods described), the CTAS En Route TP looks up the location of the parsed waypoints in its adaptation database (see Section 3.3) to convert this route into a series of lateral constraints (i.e., turn waypoints). All turn waypoints are considered "Inside Turn" Waypoints (see Section 4.2.2.1.2).

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<sup>3</sup> Lat/Lon and FRD locations are not converted into intermediate waypoints, but are turned directly into lateral constraints.

#### 4.1.1.2. Waypoint “In Front of” Aircraft State

To determine if a waypoint is “in front of” the aircraft’s initial position, a course tolerance check is performed. First, the true course from the aircraft initial position to the waypoint is calculated. If this course is within +/- 90 degrees of the aircraft’s initial condition course, then the waypoint is considered in front of the aircraft.

#### 4.1.1.3. First Route Waypoint “In Front of” Aircraft State

When the aircraft’s lateral path is based on the aircraft’s flight plan route, the CTAS En Route TP identifies which waypoint in the parsed route is “in front of” the aircraft (i.e., which is the next waypoint the aircraft will cross if flying the route). First, the aircraft’s initial condition is projected onto each segment of the parsed flight plan route (i.e., each line segment defined by two adjacent waypoints) starting at the beginning of the flight plan route. The first segment that meets the following criteria is considered the current segment of the aircraft:

- perpendicular projection of initial position is on the segment
- distance between the second waypoint (end of the segment) and the initial position is greater than or equal to 3 nmi.
- difference between the initial condition track (course) and the segment course (from the first waypoint to the second waypoint) is less than 10 degrees

The waypoint that defines the end of the current segment (i.e., of the two waypoints that define the route segment, the waypoint that is later in the route) is the first route waypoint in front of the aircraft’s initial position. The aircraft’s remaining flight plan route is defined as all parsed route waypoints past (i.e., later in the route than) this first waypoint.

#### 4.1.1.4. Capture Waypoint

A capture waypoint is defined as the point at which the aircraft recaptures the flight plan route from a position that may not lie on the route. Capture waypoints are defined as (user-specified) inputs to the CTAS En Route TP. Several lateral path modes (see next section) use the concept of a capture waypoint to transition directly or indirectly from the initial condition to the flight plan route.

Any type of waypoint can be used as capture waypoint. Only the following types of waypoints actually result in a successful transition back to the flight plan route:

- a waypoint within the Host AK route, when AK route parsing is being used
- the aircraft’s metering fix (if any)
- a waypoint within the CTAS parsed route
- a waypoint that overlays the CTAS parsed route
- a PAR transition fix
- a non-transition fix waypoint in a PAR
- an waypoint that overlays the PAR

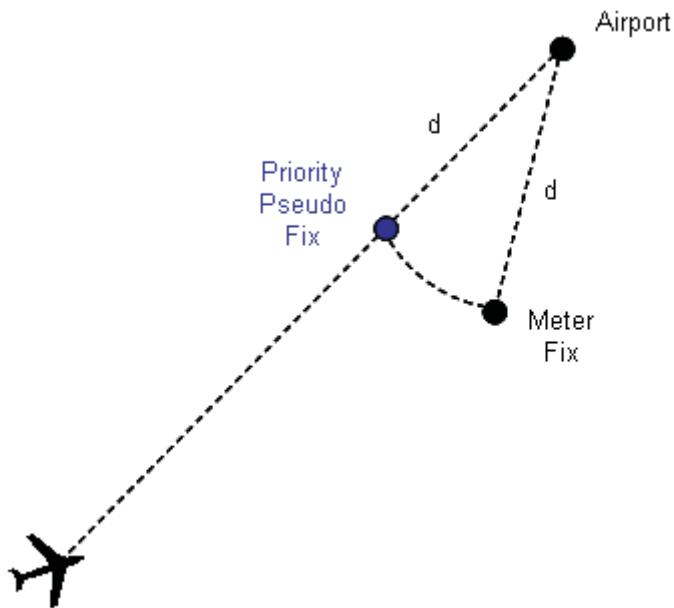
#### 4.1.1.5. Auxiliary Waypoints

To define a temporary deviation from the aircraft's flight plan route, a controller can enter a series of auxiliary waypoints (maximum of five). These waypoints can be defined at arbitrary airspace locations and represent a user defined path prior to re-capturing the flight plan path. Recapturing of the flight plan path is automatically performed by identifying the first flight plan waypoint "in front of" the last auxiliary waypoint (see Section 4.1.1.2) except the inbound course to the last auxiliary waypoint is used in place of the aircraft's initial course.

Since each auxiliary waypoint is an "Inside Turn" turn waypoint, the use of auxiliary waypoints creates a "Follow Flight Plan" Lateral Path mode (see Section 4.1.1.7). Since the aircraft's initial track will rarely be pointing directly at the first auxiliary waypoint, this will excite the "Turn to Capture Waypoint" sub-mode of this Path mode to capture the first auxiliary waypoint "in front of" of the aircraft's initial position (see Section 4.1.1.2).

#### 4.1.1.6. Priority Pseudo-Fix Generation

When an aircraft is identified as a Priority aircraft by the controller, the path of the aircraft is assumed to go straight to the airport. To support the en route portion of this path, the CTAS En Route TP translates the aircraft's current meter fix position to a point along the direct path to the aircraft (see Figure 4.1.1.6-1). The aircraft's path is assumed to immediately turn to proceed directly to this fix.



**Figure 4.1.1.6-1 Generation of Priority Pseudo-Fix**

#### 4.1.1.7. Lateral Modes

There are four basic lateral modes within the CTAS TP. They are presented, with their sub-modes and component modes, in Table 4.1.1.7-1. Some modes can transition into other modes as presented in Table 4.1.1.7-2 and as illustrated in Figure 4.1.1.7-1. Table 4.1.1.7-2 also presents the initial conditions under which the mode is selected as the first lateral mode and the conditions under which mode switches occur.

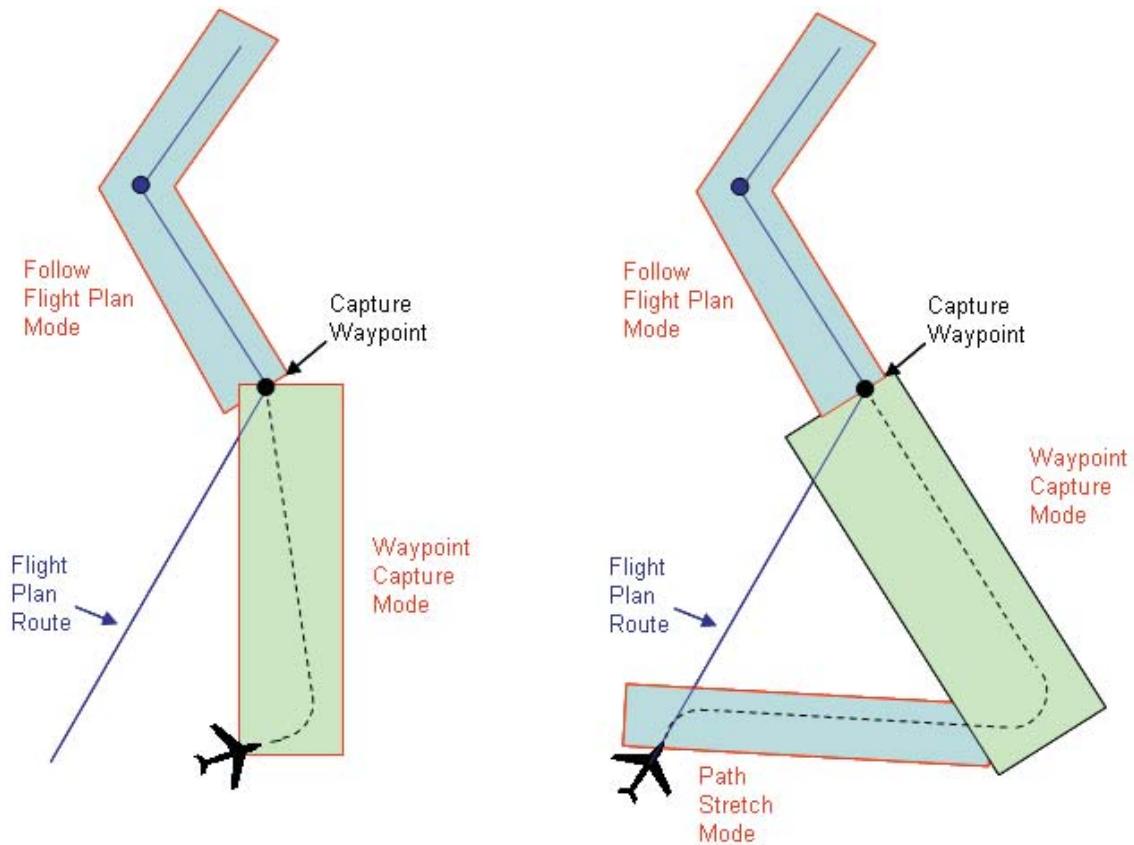
It should be noted that the Priority Lateral Mode is just a special case of a Waypoint Capture Lateral mode (where the Capture Waypoint is automatically generated) and as such, is described as an “immediate mode switch” to Waypoint Capture.

Mode	Sub/Component Modes
<b>Follow Flight Plan</b>	<b>Turn to Capture Waypoint</b> <b>Straight to Turn Waypoint</b> <b>Turn</b>
<b>Waypoint Capture</b>	<b>Delay Before Capture Turn</b> <b>Turn to Capture Waypoint</b> <b>Straight to Turn Waypoint</b>
<b>Path Stretch</b>	<b>Capture Heading</b> <b>Delay Before Capture Turn</b>
<b>Priority</b>	<b>None (See Table 4.1.1.3-2)</b>

**Table 4.1.1.7 – 1 CTAS En Route TP Lateral Modes**

Mode	Initial Condition	Next Mode Switch	Mode Switch Condition
<b>Priority</b>	<b>User Directed Mode – Priority Aircraft</b>	<b>Waypoint Capture</b>	<b>Initial Condition</b>
<b>Waypoint Capture</b>	<b>User Directed Mode – Waypoint Capture, OR No User Directed Mode and Aircraft State Off Flightplan Route</b>	<b>Follow Flight Plan</b>	<b>At the Capture Waypoint</b>
<b>Path Stretch</b>	<b>User Input – Path Stretch</b> <b>Advisory Mode</b>	<b>Waypoint Capture</b>	<b>After path stretch delay</b>
<b>Follow Flight Plan</b>	<b>No User Directed Mode and Aircraft State On Flightplan</b>	<b>None</b>	<b>N/A</b>

**Table 4.1.1.7 - 2 CTAS En Route TP Lateral Mode Switching**



**Figure 4.1.1.7-1 CTAS En Route TP Lateral Mode Switching**

Table 4.1.1.7-3 describes the required input data for each mode.

Mode	Required Input Data
<b>Follow Flight Plan</b>	<b>Flight Plan Route String and Host AK Data</b> <b>Observed Turn Radius</b>
<b>Waypoint Capture</b>	<b>Flight Plan Route String and Host AK Data</b> <b>Capture Waypoint</b> <b>Auxiliary Waypoint(s) (if any)</b> <b>Observed Turn Radius</b>
<b>Path Stretch</b>	<b>Flight Plan Route String and Host AK Data</b> <b>Capture Waypoint</b> <b>Auxiliary Waypoint(s) (if any)</b> <b>Turn Out Course</b> <b>Waypoint Capture Delay Time</b> <b>Observed Turn Radius</b>
<b>Priority</b>	<b>Flight Plan Route String and Host AK Data</b> <b>Observed Turn Radius</b>

**Table 4.1.1.7 – 3 CTAS En Route TP Lateral Mode Required Input Data**

#### 4.1.2. Vertical Path Constraint Identification

##### 4.1.2.1. Identification of Cruise Altitude

The cruise altitude is set to either the input new cruise altitude (if available) or the filed cruise altitude.

##### 4.1.2.2. Identification of Speed Constraints

The determination of speed values during cruise, climb, step descents, and descents is often a major source of intent modeling within the CTAS En Route TP. Speeds are typically determined from one of three methods:

- Identification of an advisory speed value to meet a defined objective (e.g., selection of a Descent Mach and Descent CAS to achieve a desired meter fix crossing time).
- Selection of a maximum, minimum, nominal or pre-determined speed relationship (e.g., defining the cruise speed based on descent speed value) to support either advisory generation or trajectory limits (e.g., FAST or SLOW procedures).
- Use of a defined input value (e.g., when a controller enters a cleared or desired speed)
- Modeling default airline/pilot procedural speeds (mainly used in non-advisory generation situations).

The first situation is part of advisory generation and is treated as an input value (third situation – see below) to the CTAS En Route TP.<sup>4</sup> The second and fourth situations involve intent modeling and are described under Section 4.1.3.13 below.

The third situation includes direct inputs of cruise speed, climb speed profile (Climb CAS and/or Climb Mach), and/or descent speed profile (Descent Mach and/or Descent CAS). The situations under which these speed are defined are described next. The possibility of “over-riding” these input values based on aircraft performance model speed limits is discussed under Intent Modeling (Section 4.1.3).

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<sup>4</sup> Some meet-time speed advisory modes were originally implemented within the CTAS’s TS process, but even these have been moved out into the client application. The speed constraints from these applications are just input value constraints to the TP.

#### Cruise Speed:

The cruise speed can be input as either a Cruise CAS or a Cruise Mach. If entered as a Cruise CAS, then the Cruise CAS is set to the input value and the Cruise Mach is calculated from the input Cruise CAS at the cruise altitude. If the input cruise speed is a Mach number, then the Cruise Mach is set to the input value and the Cruise CAS is calculated from the input Cruise Mach number at the cruise altitude.

#### Climb Speed Profile:

The Climb Mach and the Climb CAS can be input to the CTAS En Route TP independently. Any combination of these two parameters can be input.

#### Descent Speed Profile:

The Descent CAS and the Descent Mach can be input to the CTAS En Route TP independently. Any combination of these two parameters can be input.

##### *4.1.2.1. Vertical/Speed Modes*

There are four basic vertical/speed modes within the CTAS En Route TP. They are presented, with their sub-modes and component modes, in Table 4.1.2.3-1. These four modes can be combined into one of eight different “profiles” as presented in Table 4.1.2.3-2 and illustrated in Figures 4.1.2.3-1 through 4.1.2.3-4. Table 4.1.2.3-2 also presents the initial conditions that create each profile and the mode switch conditions for that profile.

The aircraft’s initial altitude (IA) is the initial condition (state) altitude. The cruise altitude (CA) is either the filed cruise altitude or an input new cruise altitude. The final altitude (FA) for Arrivals (including Satellite, Satellite Arrivals, Satellite Departure, Departure Arrivals and External to Satellite) is the meter fix crossing constraint. For Departures (including Satellite to External) and Overflights, the Final Altitude is the aircraft’s cruise altitude (either filed or new cruise altitude).

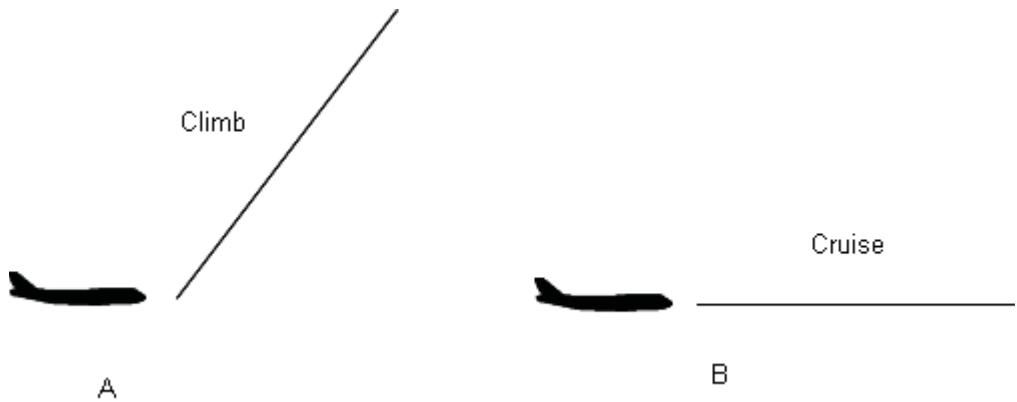
		Sub/Component Modes
Mode		
Climb	<b>Climb Below 250kt Speed</b>	<b>Capture Climb Speed Below 250Kt Altitude</b>
	<b>Limit Altitude</b>	<b>Constant CAS Climb Below 250Kt Altitude</b>
	<b>Climb Below M/CAS</b>	<b>Capture Climb Speed Below M/CAS Altitude</b>
	<b>Transition Altitude</b>	<b>Constant CAS Climb Below M/CAS Altitude</b>
	<b>Climb Above M/CAS</b>	<b>Constant Mach Climb</b>
	<b>Transition Altitude</b>	
Cruise	<b>Capture Cruise Speed</b>	<b>Accelerate to Cruise Speed</b>
		<b>Decelerate to Cruise Speed</b>
	<b>Level, Constant Speed Cruise</b>	
	<b>Capture Target Speed</b>	<b>Accelerate to Target Speed</b>
		<b>Decelerate to Target Speed</b>
Step	<b>Constant Mach Step</b>	
Descent	<b>Constant CAS Step</b>	
	<b>Idle CAS Step</b>	
Descent	<b>Fixed TOD Descent</b>	<b>Capture Descent CAS</b>
		<b>Accelerate to Descent CAS</b>
		<b>Decelerate to Descent CAS</b>
		<b>Capture Bottom of Descent</b>
		<b>Capture Crossing Restriction CAS</b>
		<b>Accelerate to Crossing CAS</b>
		<b>Decelerate to Crossing CAS</b>
	<b>Predicted TOD Descent</b>	<b>Capture Descent Speed</b>
		<b>Accelerate to Descent Speed</b>
		<b>Decelerate to Descent Speed</b>
		<b>Mach Acceleration in Descent</b>
		<b>CAS Acceleration in Descent</b>
		<b>Constant Mach Descent</b>
		<b>Constant CAS Descent</b>
		<b>Capture Crossing Restriction CAS</b>
		<b>Accelerate to Crossing CAS</b>
		<b>Decelerate to Crossing CAS</b>

**Table 4.1.2.3 – 1 CTAS En Route TP Vertical/Speed Modes**

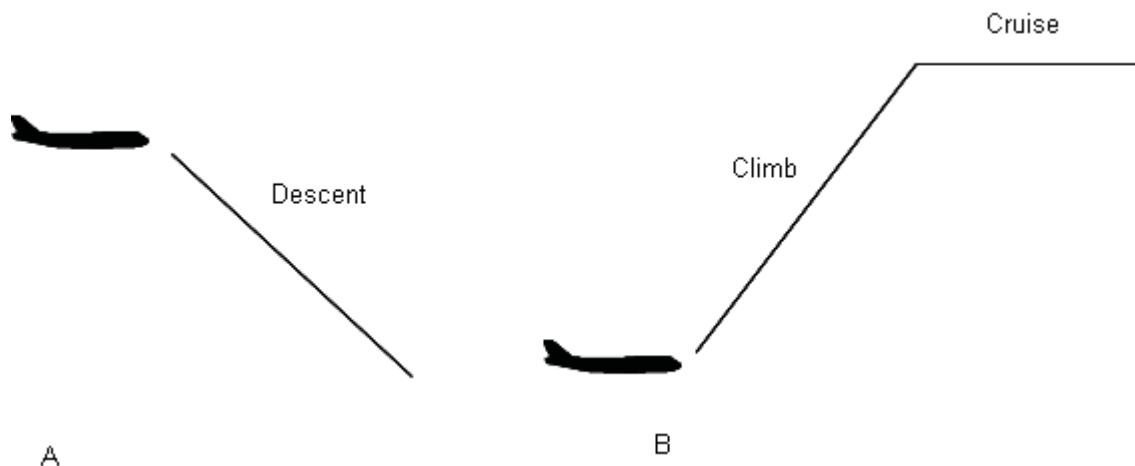
Profile	Modes	Input Conditions	Mode Switch
Climb Only	Climb	IA < FA (no CA defined) IA < CA < FA IA = CA = FA IA > FA (no CA defined) IC in descent	None
Cruise Only	Cruise		None
Descent Only	Descent		None
Climb Then Cruise	Climb Cruise	IA < CA = FA	When altitude reaches the cruise altitude ("top of climb")
Step Then Cruise	Step Descent Cruise	IA > CA and FA = CA Special Case: Overflight with IA > FA (no CA defined)	When altitude reaches cruise altitude ("end of step")
Climb, Cruise, Then Descent	Climb Cruise Descent	IA < CA and FA < CA	1: When altitude reaches the cruise altitude ("top of climb") 2: When reach the top of descent for an efficient descent
Cruise Then Descent	Cruise Descent	IA = CA and FA < CA	When reach the top of descent for an efficient descent
Step, Cruise, then Descent	Step Descent Cruise Descent	IA > CA > FA	1: When altitude reaches cruise altitude ("end of step") 2: When reach the top of descent for an efficient descent

IA = Initial Altitude; CA = Cruise Altitude; FA = Final Altitude; IC = Initial Condition

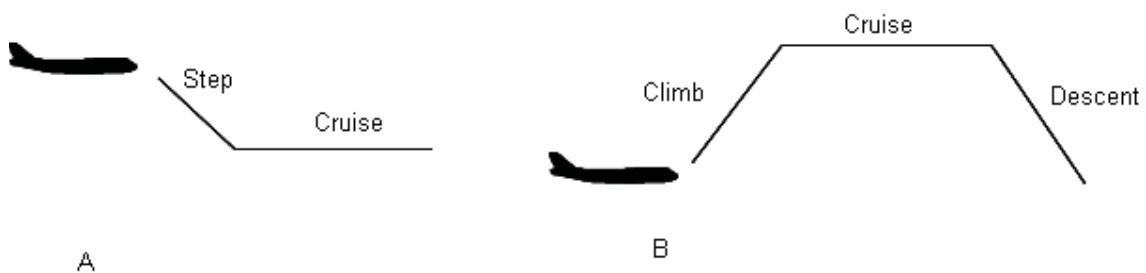
**Table 4.1.2.3-2: CTAS En Route TP Vertical/Speed Mode Switching**



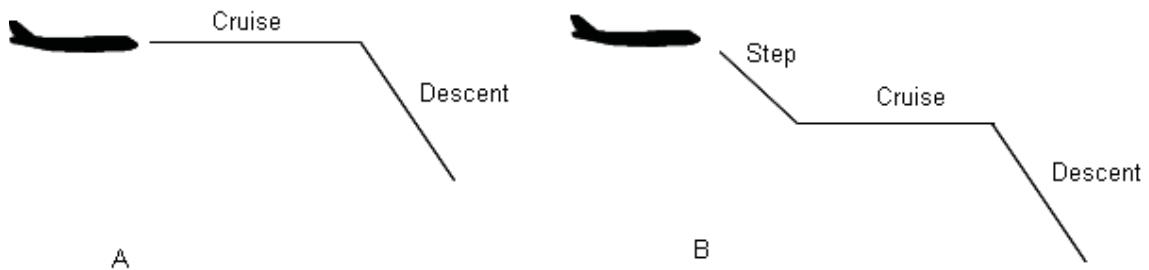
**Figure 4.1.2.3-1:** “Climb Only” (A) and “Cruise Only” (B) Profiles



**Figure 4.1.2.3-2:** “Descent Only” (A) and “Climb Then Cruise” (B) Profiles



**Figure 4.1.2.3-3:** “Step Then Cruise” (A) and “Climb, Cruise, Then Descent” (B) Profiles



**Figure 4.1.2.3-4** “Cruise Then Descent” (A) and “Step, Cruise, Then Descent” (B) Profiles

Table 4.1.2.3-3 describes the required input data for each mode.

Mode	Required Input Data
<b>Climb</b>	<b>Flight Plan Route String and Host AK Data</b> <b>Altimeter Setting</b> <b>Filed Cruise Altitude</b> <b>New Cruise Altitude</b> <b>Climb Mach Constraint</b> <b>Climb CAS Constraint</b> <b>Speed Limiter Mode</b> <b>No Initial Track Received</b> <b>Override Initial Condition CAS</b> <b>Adaptive Thrust Modeling</b>
<b>Cruise</b>	<b>Flight Plan Route String and Host AK Data</b> <b>Filed Cruise Altitude</b> <b>New Cruise Altitude</b> <b>Filed Cruise Speed</b> <b>Cruise Speed Constraint</b> <b>Speed Limiter Mode</b> <b>No Initial Track Received</b> <b>Cruise Speed Mode</b>
<b>Step Descent</b>	<b>Flight Plan Route String and Host AK Data</b> <b>Filed Cruise Altitude</b> <b>New Cruise Altitude</b> <b>Filed Cruise Speed</b> <b>Cruise Speed Mode</b>
<b>Descent</b>	<b>Flight Plan Route String and Host AK Data</b> <b>Reference Waypoint Position and Elevation</b> <b>Altimeter Setting</b> <b>Descent Mach Constraint</b> <b>Descent CAS Constraint</b> <b>Descent Weight</b> <b>Crossing Altitude Restriction</b> <b>Crossing Speed Restriction</b> <b>Descent Speed Mode</b>

**Table 4.1.2.3 – 3 CTAS En Route TP Vertical Mode Required Input Data**

#### 4.1.3. Intent Modeling

##### **Lateral**

###### *4.1.3.1. Aircraft Initial Position Not on Flight Plan Route*

When the initial position of the aircraft does not meet the criteria described in Section 4.1.1.3 to be considered “on” any of the parsed flight plan route segments, the lateral path defaults to one of the following:

- If AK route parsing is being used, the trajectory fails.
- If not using AK route parsing and the first route point is not in front of the aircraft's initial position (see Section 4.1.3.2), the aircraft is assumed to be in "Waypoint Capture" Lateral Path mode with the route's final waypoint in this center as the capture waypoint:
  - For Arrival, Satellite, Satellite Departure and External to Satellite aircraft, captures the metering fix (or airport location if no metering fix)
  - For Overflight, Satellite to External, and Departure aircraft, captures the ARTCC boundary crossing

#### *4.1.3.2. Aircraft Initial Position "Outside" Route*

If the aircraft's initial position is "outside" the flight plan route (i.e., the first waypoint of the route, typically a coordination fix, is "in front of" the aircraft as per Section 4.1.1.2), then the lateral path is modeled as an immediate turn to capture the first route waypoint and then follows the route. The Lateral mode is "Follow Flight Plan" Lateral Path mode (see Section 4.1.1.7). If the aircraft's initial track is not pointing directly at the first route waypoint, this will excite the "Turn to Capture Waypoint" sub-mode of this Lateral Path mode to capture the first route waypoint. The first route waypoint is assumed to be an "Inside Turn" turn waypoint.

#### *4.1.3.3. Capture Waypoint Does Not Transition to Flight Plan Route*

When an input Capture Waypoint is NOT one of the types described in Section 4.1.1.4, the Capture Waypoint does not enable transition to the flight plan route. In these cases, the aircraft lateral path is determined using the same method as described in Section 4.1.3.1.

#### *4.1.3.4. Aircraft Initial Position "Too Close" to Capture Waypoint*

If the aircraft's initial position gets within 5 nmi of the Capture Waypoint, the next waypoint in the route is used for capture.

#### *4.1.3.5. Outbound Course at Meter Fix*

The outbound course at the metering fix for an arrival aircraft is determined from a CTAS defined nominal TRACON route. These routes are constructed based on nominal TRACON procedures and are a function of several variables including arrival runway, metering fix, and aircraft class.

#### *4.1.3.6. Delay Time Before Waypoint Capture*

If a Capture Waypoint is defined within the route, but a Waypoint Capture Delay Time is not specified, a value of 15 seconds is used.

#### *4.1.3.7. Use Observed Turn Radius*

Overrides the calculation of an estimated turn radius (based on initial ground speed) at the aircraft's initial condition with a turn radius value determined from observation.

## **Vertical**

### 4.1.3.8. Flight Plan Altitude

If the filed altitude in the Host flight plan is invalid or is a VFR altitude, then this altitude is set to a default value. This default value is either the aircraft's metering fix crossing restriction altitude, if the aircraft is an arrival and has a valid metering fix, or is set to 33000 ft.

### 4.1.3.9. Procedural Altitudes

#### 4.1.3.9.1. M/CAS Transition Altitude

The M/CAS Transition Altitude (MCTA) is a procedural altitude above which the aircraft is assumed to be cruising at a constant Cruise Mach number. Below this altitude, the aircraft is assumed to cruise at constant Cruise CAS. This altitude is calculated from the Climb Speed Profile.

If the aircraft initial condition is in a Climb, the M/CAS Transition Altitude is calculated as the altitude at which the aircraft is simultaneously at both the Climb CAS and Climb Mach from its Climb Speed Profile. This calculation is done assuming a standard atmosphere.

If the aircraft initial condition is not in a Climb and a Climb Mach input was received, the M/CAS Transition Altitude is calculated as the altitude at which the aircraft is simultaneously at both the aircraft model's default Climb CAS and the input Climb Mach. This calculation is done assuming a standard atmosphere.

If the aircraft initial condition is not in a Climb and no Climb Mach input was received, the M/CAS Transition Altitude is calculated using the following algorithm:

1. Calculate the CAS at 10,000 ft if the aircraft were at the aircraft model's maximum Mach number using the full weather model at the aircraft initial position.
2. Calculate the CAS at 35,000 ft if the aircraft were at the aircraft model's maximum Mach number using the full weather model at the aircraft initial position.
3. Assuming a linear variation of CAS with altitude for the aircraft model's maximum Mach number, determine the altitude at which the aircraft model's default Climb CAS is equal to the maximum Mach Number
4. This M/CAS Transition altitude is set equal to this altitude

#### 4.1.3.9.2. Descent Transition Altitude

The Descent Transition Altitude (DTA) is determined from the Descent Speed Profile and represents the altitude above which the aircraft uses Mach number within its descent procedures. This altitude is defined as the altitude at which the aircraft is simultaneously at both the Descent Mach and Descent CAS from its Descent Speed Profile.

This altitude is not typically calculated directly, but a calculation to determine whether the aircraft is above this altitude is performed:

1. Calculate the equivalent Mach number for the Descent CAS at the cruise altitude

2. If this value is greater than or equal to the Descent Mach, then the aircraft initial condition is above the Descent Transition Altitude

#### *4.1.3.9.3. 250 kt Speed Limit Altitude*

Altitude below which the aircraft's CAS is not allowed to exceed 250 kts. The CTAS En Route TP uses 10,000 ft for this altitude.

#### *4.1.3.9.4. Altitude Cutoff for Minimum CAS*

Altitude above which the aircraft's CAS is not allowed to be below the aircraft model's minimum CAS value. Also used to determine when the aircraft's initial CAS is not allowed to be below the Climb CAS. The CTAS En Route TP uses 20,000 ft for this altitude.

#### *4.1.3.10. Initial Condition Speeds*

If the aircraft initial condition is in a Climb, the initial condition speeds are checked against input and aircraft model default climb speeds for consistency. In the following situations, the input initial condition speeds are overridden:

1. The CTAS TP can be requested (Override Initial Condition CAS input) to replace the initial CAS by the aircraft model default Climb CAS. The initial Mach, initial TAS, and initial Groundspeed are all calculated from the Climb CAS at the initial altitude.
2. If the initial altitude is less than the 250 kt Speed Limit Altitude and the initial CAS is greater than 250 kts
  - the initial CAS is set to 250 kts; and
  - the initial Mach, initial TAS, and initial Groundspeed are all calculated from 250 kts at the initial altitude.
3. If the initial altitude is greater than the 250 kt Speed Limit Altitude, but less than the M/CAS Transition Altitude and using the input Speed Limiter Mode, and:
  - if the initial CAS is greater than the Climb CAS; OR
  - if the initial CAS is less than the Climb CAS and the initial altitude is above the Altitude Cutoff for Minimum CASthen the initial CAS is set to the Climb CAS and the initial Mach, initial TAS, and initial Groundspeed are all calculated from the Climb CAS at the initial altitude.
4. If the initial altitude is above the M/CAS Transition Altitude, using the input Speed Limiter Mode, and the initial Mach is not equal to the Climb Mach, then the initial Mach is set equal to the Climb Mach and the initial CAS, initial TAS, and initial Groundspeed are all calculated from the Climb Mach at the initial altitude.

If the aircraft initial condition is in Cruise, then if using the input Speed Limiter Mode, the aircraft initial Mach and CAS are compared against the aircraft model's limiting speeds. If the initial Mach/CAS is greater than either the aircraft model's maximum cruise Mach or maximum cruise CAS (whichever is more restrictive), then the initial Mach or CAS is set to the aircraft model's limiting value. If the initial altitude is above the Altitude Cutoff for Minimum CAS and the initial CAS is less than the aircraft model's minimum cruise CAS, then the initial CAS is set to the

aircraft model's minimum cruise CAS. In all situations, the other initial condition speeds (Mach, CAS, TAS, and Groundspeed) are all calculated from the limited speed at the initial condition altitude.

The same logic used when the initial condition is in Cruise is used if the initial condition is in a Descent except that the aircraft model's minimum and maximum CAS and Mach values are used instead of the aircraft model's minimum and maximum cruise CAS and Mach values.

#### *4.1.3.11. Final (Meter Fix) Crossing Restriction Altitude and CAS*

After completion of the flight plan route parsing, the parsed route is searched for a waypoint that is also a CTAS adapted metering fix. If a metering fix is found, the crossing restriction altitude and speed (CAS) is looked up in a database of adapted letters of agreement between the ARTCC and TRACON/Satellite Airport facilities.

After retrieving the adapted letters of agreement data, additional intent modeling is applied to the crossing restriction CAS.

If using the input Speed Limiter Mode, the aircraft crossing restriction CAS (and associated Mach) are compared against the aircraft model's limiting speeds. If the crossing restriction CAS is greater than either the aircraft model's maximum cruise CAS or cruise Mach (whichever is more restrictive), then the crossing restriction CAS is set to the aircraft model's limiting value. If the crossing altitude is above the Altitude Cutoff for Minimum CAS and the crossing restriction CAS is less than the aircraft model's minimum cruise CAS, then the crossing restriction CAS is set to the aircraft model's minimum cruise CAS. In all situations, the other crossing restriction speeds (Mach, TAS, and Groundspeed) are all calculated from the limited speed at the crossing restriction altitude.

If no crossing restriction CAS is input to the CTAS En Route TP, the crossing restriction CAS is set to the NOMINAL Descent CAS.

#### *4.1.3.12. Cruise Altitude*

If a new cruise altitude greater than 60,000 ft is entered, the CTAS En Route TP returns an error.

#### *4.1.3.13. Profile Speeds*

##### *4.1.3.13.1. Cruise Speed*

There are several different input Cruise Speed Modes the client application can use to impact the modeling of Cruise Mach and Cruise CAS within the CTAS En Route TP. Each is discussed below, as is the default modeling if no inputs are provided. It should be noted that calculation of a cruise speed is only performed if the trajectory profile (see Section 4.1.2.3) contains a Cruise Mode.

### Maximum Value

The limiting speed (Cruise Mach or Cruise CAS) is determined as the minimum of<sup>5</sup> the:

- maximum cruise Mach from the aircraft model
- maximum cruise CAS from the aircraft model

The other speed (Cruise Mach or Cruise CAS) is calculated from the limiting speed at the cruise altitude.

### Minimum Value

The Cruise CAS is set to the minimum cruise CAS from the aircraft model. The Cruise Mach is calculated from the Cruise CAS at the cruise altitude.

### Minimum Cruise or Descent CAS

The limiting CAS is determined as the minimum of the:

- minimum cruise CAS from the aircraft model
- minimum CAS from the aircraft model

The Cruise CAS is set equal to the limiting CAS. The Cruise Mach is calculated from the Cruise CAS at the cruise altitude.

### Input Value

As described in Section 4.1.2.2 above, input cruise speed values can be limited by aircraft performance model speed limits within the CTAS En Route TP. This occurs when an input Cruise CAS exceeds the maximum cruise Mach from the aircraft model. In this case, the input value is reduced to the aircraft model's maximum cruise Mach.

### Minimum of Current Cruise or Input Value

Uses the smaller of an Input Value (see processing above) or the Default Modeling (see below).

### Default Modeling

The three types of trajectories that can be requested of the CTAS En Route TP (FAST, NOMINAL, SLOW) each have their own modeling of how to set the cruise speed:

*FAST Cruise Speed Modeling:* Uses an Input Value if available. If not available, then the Maximum Value is used. The only exception to this is if the aircraft is currently in cruise and its current speed is greater than the maximum value, in which case the current speed is used for the cruise speed.

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<sup>5</sup> Whenever a Mach is compared to a CAS to determine a minimum or maximum speed, the Mach is converted to a CAS at an appropriate altitude (in this case, the cruise altitude) and then the comparison is performed. In cases where both the Mach and CAS are needed after the comparison is complete, the limiting value (Mach or CAS) is converted to the other speed type at the appropriate altitude.

*SLOW Cruise Speed Modeling:* Uses an Input Value if available. If not available, then the Minimum Value is used. The only exception to this is if the aircraft is currently in cruise and its current speed is less than the minimum value, in which case the current speed is used for the cruise speed.

*NOMINAL Cruise Speed Modeling:* Uses an Input Value if available. If not available, then the cruise speed is determined from the aircraft's initial state:

*In Climb:* If a cruise TAS is available in the flight plan, then the Cruise CAS and Cruise Mach are calculated from this TAS. There is an option (Speed Limiter Mode) to limit the calculated Cruise CAS and Cruise Mach by the aircraft model speed limits (minimum cruise CAS, maximum cruise CAS, maximum cruise Mach), if necessary. If no input cruise TAS is available, the Cruise CAS is estimated from aircraft model parameters as:

$$\text{CruiseCAS} = \text{CAS}_{\min} + \frac{2}{3}(\text{CAS}_{\max} - \text{CAS}_{\min})$$

where  $\text{CAS}_{\max}$  is the aircraft model's maximum cruise CAS (limited by the aircraft model's max cruise Mach, if necessary) and  $\text{CAS}_{\min}$  is the aircraft model's minimum cruise CAS (set equal to  $\text{CAS}_{\max}$  if  $\text{CAS}_{\max}$  is less than  $\text{CAS}_{\min}$ ).

*In Cruise and Performing a Step Descent:* Uses the aircraft model's default Descent CAS as the Cruise CAS, limited by the aircraft model's maximum cruise Mach, if necessary. The Cruise Mach is calculated from the Cruise CAS at the cruise altitude.

*In Cruise (no Step Descent):* Uses the initial condition Mach and CAS as the Cruise Mach and Cruise CAS.

#### 4.1.3.13.2. *Climb Speed Profile*

The same algorithm is used for the climb speed profile (Climb CAS and Climb Mach) independent of the type of trajectory requested of the CTAS En Route TP (FAST, NOMINAL, SLOW). It should be noted that calculation of a cruise speed is only performed if the trajectory profile (see Section 4.1.2.3) contains a Climb Mode.

##### *Climb CAS*

If an input Climb CAS is not available, the aircraft model default Climb CAS is used.

The Climb CAS determined above is overridden if

- the initial altitude is above the Altitude Cutoff for Minimum CAS, but below the M/CAS Transition Altitude; OR

- the initial altitude is above the 250kt Speed Limit Altitude, but below the M/CAS Transition Altitude and the initial condition CAS is greater than (or equal to) the Climb CAS

In these cases, the Climb CAS is set equal to the initial condition CAS.<sup>6</sup>

#### *Climb Mach*

If an input Climb Mach is available and it is less than the Cruise Mach, then the input Climb Mach is used. In all other cases, the Climb Mach is set to the Cruise Mach.

The Climb Mach determined above is overridden if

- the initial altitude is above the Altitude Cutoff for Minimum CAS, but below the M/CAS Transition Altitude; OR
- the initial altitude is above the 250kt Speed Limit Altitude, but below the M/CAS Transition Altitude and the initial condition CAS is greater than (or equal to) the Climb CAS

In this case, the Climb Mach is calculated from the Climb CAS at the M/CAS Transition Altitude.

The Climb Mach is also overridden if the initial altitude is above the M/CAS Transition Altitude. In this case, the Climb Mach is set equal to the initial Mach.<sup>7</sup>

#### *4.1.3.13.3. Descent Speed Profile*

##### *Descent CAS*

It should be noted that calculation of a descent speed is only performed if the trajectory profile (see Section 4.1.2.3) contains a Descent Mode.

If an input Descent CAS is available and the Descent Speed Mode is set to Input Value, then this input value is used for all trajectory types (FAST, SLOW, NOMINAL).

If another Descent Speed Mode is input, then the Descent CAS is set to:

- Maximum Value = aircraft model's maximum CAS
- Minimum Value = aircraft model's minimum CAS
- Minimum Cruise Equals Descent Value = Uses the greater of the minimum Cruise CAS and the aircraft model's minimum CAS.
- Sub Nominal Value = Use an input percentage of the aircraft model's default descent CAS

If an input Descent CAS is not available and the Descent Speed Mode is Nominal Value:

- FAST trajectory type: the Descent CAS is set to the aircraft model's maximum CAS

<sup>6</sup> It should be noted that if the input Speed Limiter Mode is requested, the initial condition CAS is set to the Climb CAS in all cases, which would eliminate the override.

<sup>7</sup> It should be noted that if the input Speed Limiter Mode capability is requested, the initial condition Mach is set to the Climb Mach in all cases, which would eliminate the override.

- SLOW trajectory type: the Descent CAS is set to the aircraft model's minimum CAS
- NOMINAL trajectory type: the Descent CAS is set to
  - the aircraft model's default descent CAS; or if not available
  - a model of a company preferred descent CAS, or if not available
  - the nominal Cruise CAS

The nominal Descent CAS is limited by the aircraft model's maximum CAS.

For all trajectory types, a final check is performed before doing a Fixed TOD Descent Sub-mode:

- if the Descent CAS is less than the initial condition CAS, AND
- the equivalent Mach number for the Descent CAS at the initial condition altitude is greater than the aircraft model's maximum Mach number,
- then the Descent CAS is reduced to the equivalent CAS for the aircraft model's maximum Mach number at the initial condition altitude.

#### *Descent Mach*

If an input Descent Mach is available, then this value is used for all trajectory types (FAST, SLOW, NOMINAL).

If an input Descent Mach is not available:

- FAST trajectory type: the Descent Mach is set to the FAST Cruise Mach
- SLOW trajectory type: the Descent Mach is set to the SLOW Cruise Mach
- NOMINAL trajectory type: the Descent Mach is set to the NOMINAL Cruise Mach

#### *4.1.3.13.4. Step Descent Speed*

The modeling of the speeds used in a Step Descent is different for Overflight and Non-Overflight aircraft.

##### *Overflight Aircraft:*

If the initial condition altitude and the new cruise altitude are both above the M/CAS Transition altitude, then the Step Descent holds the initial condition Mach number through the altitude change.

If the initial condition altitude is above, but the new cruise altitude is below the M/CAS Transition altitude, then the initial condition Mach number is held during the altitude change until reaching the M/CAS Transition altitude. At that point, CAS is held constant for the remainder of the maneuver.

##### *Non-Overflight Aircraft:*

If the following conditions hold for a Jet aircraft:

- initial altitude is greater than the cruise altitude which is greater than the final altitude,
- initial CAS is less than both the Cruise CAS and 310 kts
- initial mach is less than the Cruise Mach

then the Step Descent holds the initial condition Mach number through the altitude change.

If the following conditions hold for a Jet aircraft:

- initial altitude is greater than the cruise altitude which is greater than the final altitude,
- initial CAS is less than both the Cruise CAS and 310 kts
- initial mach is greater than or equal to the Cruise Mach

then the Step Descent holds the initial condition Mach number until capturing the smaller of the Cruise CAS or 310 kts. At that point, CAS is held constant for the remainder of the maneuver.

If the following conditions hold for a Jet aircraft:

- initial altitude is greater than the cruise altitude which is greater than the final altitude,
- initial CAS is greater than or equal to both the Cruise CAS or 310 kts

then the initial CAS is held constant throughout the altitude change.

For a Turboprop aircraft where the initial altitude is greater than the cruise altitude, which is greater than the final altitude, the initial CAS is held constant throughout the altitude change.

#### 4.1.4. Trajectory End Conditions

For CTAS TP En Route Trajectories, the trajectory end condition is always related to a point in the lateral path. The types of end conditions, based on the aircraft flight plan category, are defined in Table 4.1.4-1.

Aircraft Flight Plan Category	Trajectory End Condition
<b>Satellite</b>	<b>Satellite Airport Location</b>
<b>External to Satellite</b>	
<b>Satellite Departure</b>	
<b>Departure</b>	<b>Center Boundary</b>
<b>Satellite to External</b>	
<b>Overflight</b>	
<b>Satellite Arrival</b>	<b>Meter Fix or TRACON Boundary</b>
<b>Departure Arrival</b>	
<b>Arrival</b>	

**Table 4.1.4 Trajectory End Conditions.**

### 4.2. Trajectory Prediction Process

#### 4.2.1. Flight Script

The CTAS En Route TP does not use a form of a Trajectory Script. The implementation is such that the “interface” to the Trajectory Engine is within a larger piece of code that performs additional Preparation Processing before initiating the Trajectory Engine processing.

#### 4.2.2. Trajectory Engine

The CTAS En Route TP’s Trajectory Engine performs the following steps to generate a 4D trajectory from the modes and constraints submitted from the preparation process:

1. Generate an approximate vertical profile from the input lateral and vertical constraints

2. Identify the approximate ground speed at each turn location
3. Use the estimated ground speeds to geometrically define the 2D lateral path
4. Integrate an accurate vertical profile along the 2D lateral path
5. (Option) Second Pass to refine the horizontal path using the accurate vertical profile from the first pass.

Using this approach, the CTAS En Route TP does not integrate lateral equations of motion.

#### *4.2.2.1. Lateral Segment Definitions*

This section describes the vertical path approximation used for calculating approximate ground speeds at turn locations and describes detailed definitions of sub-mode and component mode switching for each of the lateral path modes defined in Section 4.1.1.7.

##### *4.2.2.1.1. Approximate Vertical Path Generation*

The estimated vertical path is determined as a function of along path distance,  $s$ . The goal is to determine an estimate for the ground speed at each turn waypoint for use in modeling a constant radius turn at that waypoint.

Initially,  $s$  is calculated as the distance between the input waypoints (i.e., assuming instantaneous turns at each waypoint). This provides an  $s$  value for each turn waypoint.

##### Altitude Estimation:

$S$  values for the top-of-ascent (TOA), begin-of-step (BOS), end-of-step (EOS) and top-of-descent (TOD) locations are then estimated, if applicable, from the TP input altitude constraints. All climbs and descents are estimated using a constant 3 degree inertial flight path angle. This enables the TOA, BOS, EOS and TOD estimates to be calculated solely from altitude information. This also allows any intermediate altitudes at locations between these points to be linearly interpolated. Specifically, an estimated altitude at each turn waypoint can be determined.

There are eight different profile “shapes” definable from the possible input altitude constraints. These eight shapes are illustrated in Figure 4.2.2.1.1-1.

In the following cases, the “shape” is modified to accommodate the input data:

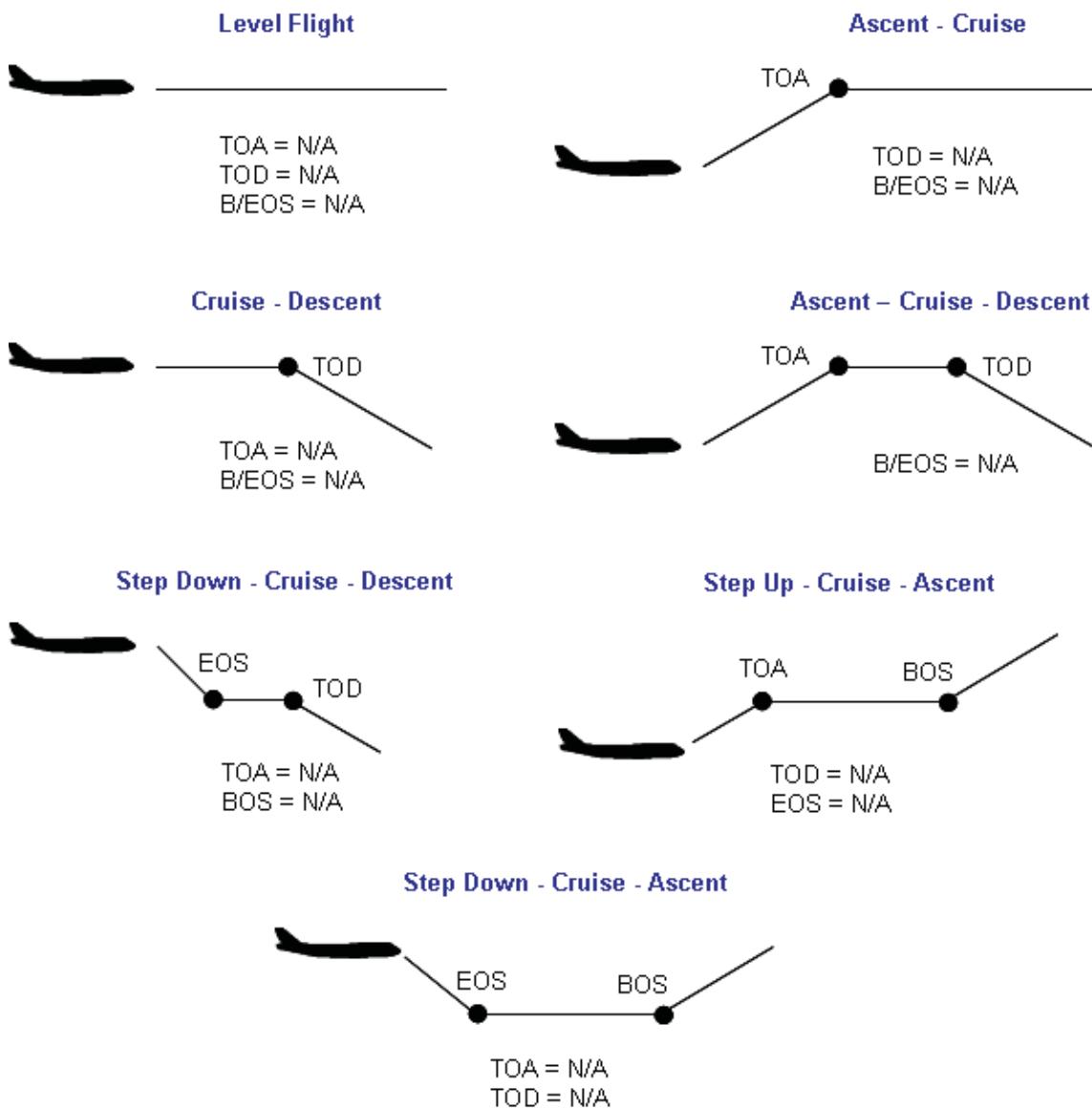
*Cruise-Descent:* If the TOD calculated from a constant 3 degree inertial flight path angle is before the aircraft’s initial position, then the TOD is set equal to the aircraft initial position and a constant inertial flight path angle from the initial condition to final condition is used.

*Ascent-Cruise-Descent:* If there is an input TOD constraint, then the TOD location is moved to this waypoint’s location. Also, if the TOD ends up before the TOA, both are set to a location equidistant between the aircraft’s initial and final conditions.

*Step Down-Cruise-Descent:* If the cruise distance (from EOS to TOD) is less than 15 nmi, then the cruise segment is ignored and the shape is changed to a Cruise-Descent shape.

*Step Up-Cruise-Ascent*:<sup>8</sup> If the BOS ends up before the TOA, then a single climb from initial condition to final condition is assumed at the required constant inertial flight path angle.

*Step Down-Cruise-Ascent*:<sup>9</sup> If the BOS ends up before the EOS, then a single climb/descent from initial condition to final condition is assumed at the required constant inertial flight path angle.



**Figure 4.2.2.1.1-1 Estimated Vertical “Shapes” Used for Lateral Path Generation**

<sup>8</sup> There is no “accurate” vertical profile (see under vertical modes) that can do this type of shape.

<sup>9</sup> This shape is not currently supported when generating the estimated ground speed

### Airspeed Estimation:

The results of the Preparation Processing of aircraft speeds are used during the estimation of the approximate vertical path. This includes all of the processing described in Section 4.1 above. For the approximate vertical path generation, only the CAS values (Climb, Descent, Cruise) are used for each section of the aircraft's altitude shape. This means that the aircraft's Climb CAS is used for all ascending segments: (1) between the initial condition and the TOA, and (2) between the BOS and the final condition. The aircraft's Descent CAS is used for all descending segments: (1) between the TOD and the final condition, and (2) between the initial condition and the EOS. The aircraft's Cruise CAS is used for all level flight segments: (1) between the initial condition and the final condition, (2) between the TOA and the final condition, (3) between the initial condition and the TOD, (4) between the TOA and the TOD, (5) between the EOS and the TOD, and (6) between the TOA and the BOS.

Since the location of each turn waypoint can be associated with a climb, cruise, or descent segment, an estimated CAS value for each turnpoint can be determined.

### Ground Speed Estimation:

For each turn waypoint, the estimated ground speed can be calculated from its estimated altitude, course and CAS values, using the atmospheric model. Ground speed approximations attempt to average the ground speed at the initiation and conclusion of each turn. Primarily, this attempts to capture the difference in wind values through the turn. Since the actual final (exit) course for certain turns is not knowable without knowing the turn radius, this course is estimated from known information.

For the ground speed at the initiation of the turn, the following values are used:

- CAS = estimated CAS at the turn waypoint position
- altitude = estimated altitude at the turn waypoint position
- course = course from previous turn waypoint to the turn waypoint

For the ground speed at the conclusion of the turn, the following values are used:

- CAS = estimated CAS at the turn waypoint position
- altitude = estimated altitude at the turn waypoint position
- course = course from the turn waypoint to the next turn waypoint

The final ground speed estimate is the average of these two ground speed estimates.

#### *4.2.2.1.2. Follow Flight Plan Mode*

Table 4.2.2.1.2-1 and Table 4.2.2.1.2-2 describe the three sub-modes of the Follow Flight Plan mode, including the switching conditions between them. Figure 4.2.2.1.2-1 graphically illustrates the possible combination of these sub- and component modes. Note that the sub-mode "Turn to Capture Waypoint" is equivalent to a "Begin Turn At" component mode, so it is not explicitly called out in the figure. Also, the Sub-mode "Straight to 'No Turn'" is also equivalent to a "Straight to 'Begin Turn At'" (without the turn at the following waypoint), so it is also not explicitly called out in the figure.

Sub-Mode	Component Modes	Applicable Cases	Capture Condition	Model	Next Sub-/Component Mode
Turn to Capture Waypoint	Turn to Capture Waypoint Position	First Turn* Waypoint is “Inside Turn” or “Begin Turn At”; IC Track > 1.2 degrees off direct to waypoint	Course to First Waypoint “Ahead” in Route	Constant Radius Turn	Straight to Turn Waypoint
	Turn to Capture “End Turn At” Waypoint	First Turn* Waypoint is “End Turn At”	Beginning of Turn at Next Waypoint		
Straight to Turn Waypoint	Straight to “Inside Turn” Waypoint	Next Turn Waypoint is “Inside Turn”	Beginning of Turn at Next Waypoint	Constant Course	Turn
	Straight to “Begin Turn At” Turn Waypoint	Next Turn Waypoint is “Begin Turn At”	Position of Next turn Waypoint		
	Straight to “End Turn At” Turn Waypoint	Next Turn Waypoint is “End Turn At”	Beginning of Turn at Next Waypoint		
	Straight to “No Turn”	Next Turn Waypoint is the Last Waypoint	Position of Next turn Waypoint		None
	See Separate Table	See Separate Table	See Separate Table	Constant Radius Turn	Straight to Turn Waypoint

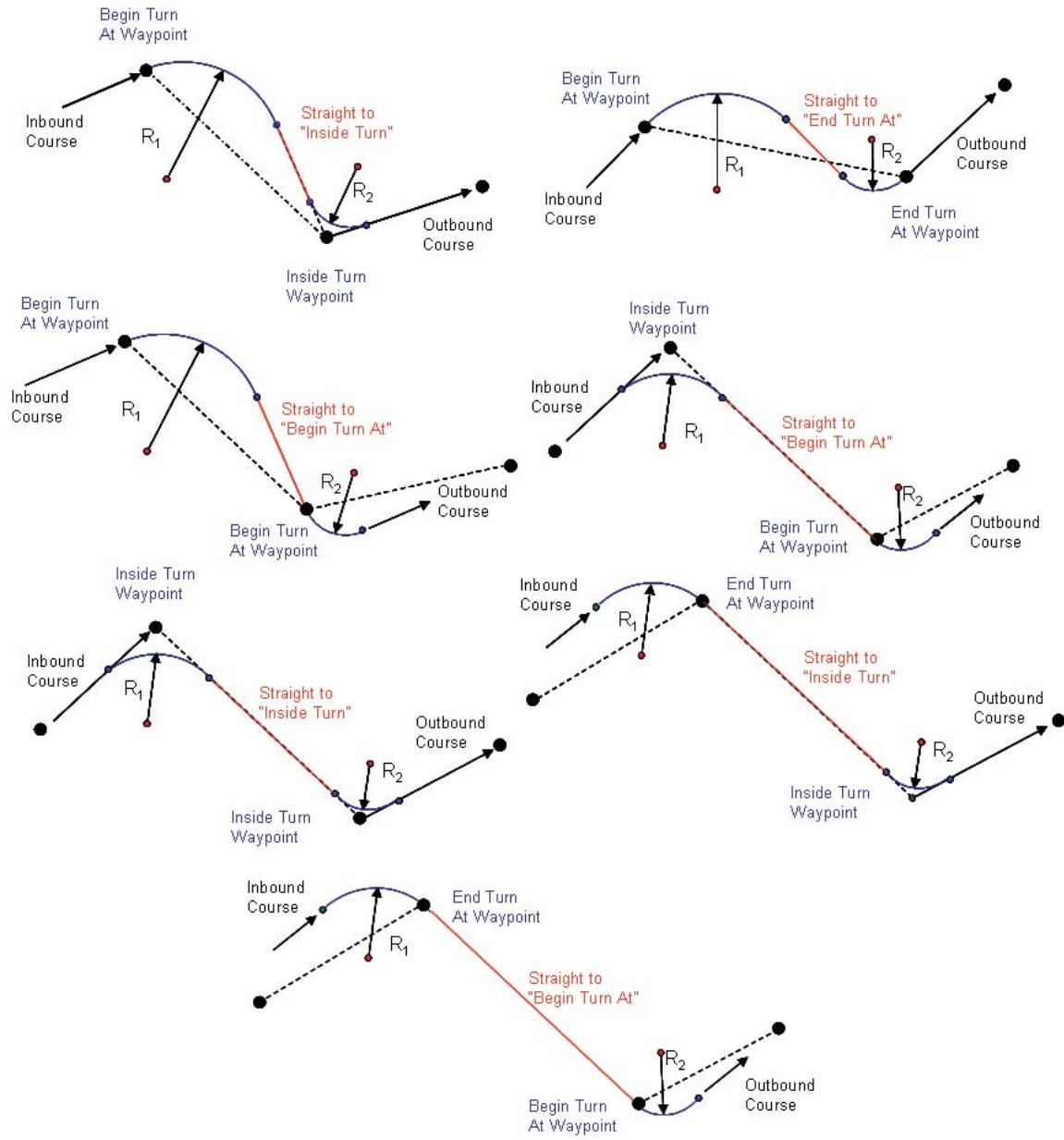
\*The first turn is the first waypoint “ahead” of the aircraft initial condition (see Preparation Process)

**Table 4.2.2.1.2-1 Sub- and Component Modes of Follow Flight Plan Mode**

Component Modes	Cases: Next Turn Waypoint	Capture Condition	Model	Next Sub-/Component Mode
<b>Inside Turn</b>	<b>Inside Turn</b>	<b>Course to Next Waypoint</b>	<b>Constant Radius Turn</b>	<b>Straight to “Inside Turn” Waypoint</b> <b>Straight to “Begin Turn At” Turn Waypoint</b>
		<b>Begin Turn At</b>		<b>Straight to “Inside Turn” Waypoint</b> <b>Straight to “Begin Turn At” Turn Waypoint</b>
<b>Begin Turn At</b>	<b>Inside Turn</b>	<b>Course to Next Waypoint</b>		<b>Straight to “Inside Turn” Waypoint</b> <b>Straight to “Begin Turn At” Turn Waypoint</b>
		<b>Begin Turn At</b>		<b>Straight to “Begin Turn At” Turn Waypoint</b>
			<b>End Turn At</b>	<b>Beginning of Turn at Next Waypoint**</b> <b>Straight to “End Turn At” Turn Waypoint</b>
<b>End Turn At</b>	<b>Inside Turn</b>	<b>Course to Next Waypoint</b>		<b>Straight to “Inside Turn” Waypoint</b> <b>Straight to “Begin Turn At” Turn Waypoint</b>
		<b>Begin Turn At</b>		<b>Straight to “Begin Turn At” Turn Waypoint</b>

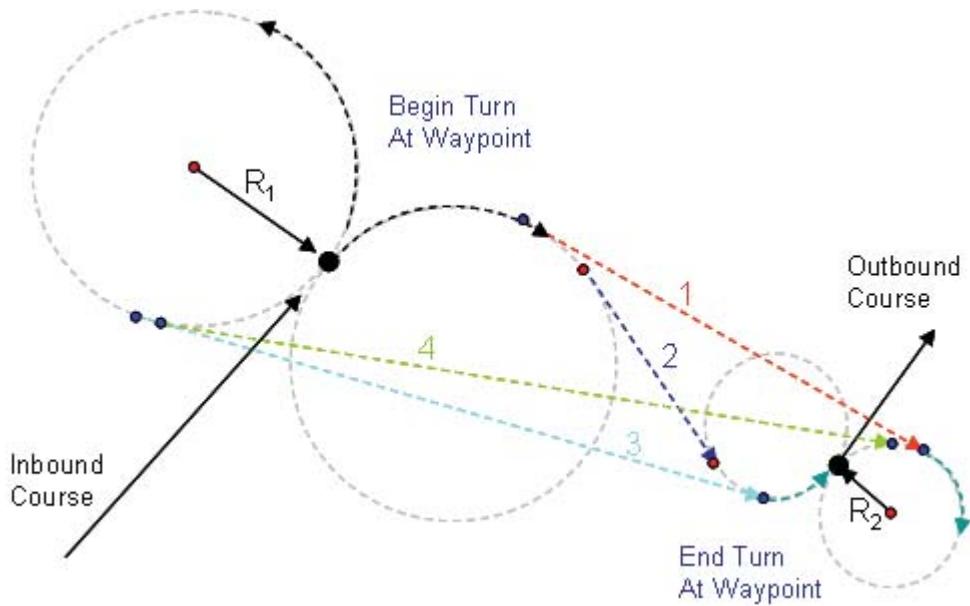
\*\* See following discussion.

**Table 4.2.2.1.2-2 Combinations of Turn Sub/Component-Modes of Follow Flight Plan Mode**



**Figure 4.2.2.1.2-1 Illustration of Combined Follow Flight Plan Sub- and Component Modes**

To calculate the final course of a “Begin Turn At” turn waypoint when followed by an “End Turn At” waypoint, a straight line that is tangent to the circles defined by the turn radii of both turns must be determined. There are four different ways in which this straight line segment can be defined (see Figure 4.2.2.1.2-2). The CTAS En Route TP chooses the straight segment path with the shortest length.



**Figure 4.2.2.1.2-2 Illustration of the Possible Straight Path Connections of a “Begin Turn At” Turn Waypoint with an “End Turn At” Turn Waypoint.**

As can be seen from Figure 4.2.2.1.2-1, there are situations where the end of a turn can overlap with the beginning of the next turn. This can happen when two turns are “too close” to each other to both be handled. In these cases, the two turns are modified as described in Section 4.2.2.1.5 below.

If an Inside Turn Waypoint requires more than a 127 degree turn, a special model is used to handle this “large turn” situation, as is described in Section 4.2.2.1.6 below.

#### Follow Flight Plan Models

##### Constant Radius Turn

As described above, the aircraft’s lateral path (including turns) is estimated geometrically in three dimensions and is not numerically integrated. The predicted time at any point along the path is calculated as part of the vertical profile segments.

All turns<sup>10</sup> within the CTAS En Route TP are modeled as constant radius turns (i.e., instantaneous bank angle changes). The turn radius is computed assuming a constant bank angle ( $\phi$ ), constant ground speed ( $V_g$ ), and no acceleration in the vertical plane. The bank angle for all en route turns is assumed to be 20.8°. The basic ground speed estimation is as described above in the Approximate Vertical Path Generation.

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<sup>10</sup> Turns which create a change in course of less than 1.2° are ignored.

Given these assumptions, the equation for the turn radius ( $R_t$ ) is:

$$R_t = \frac{V_G^2}{g * \tan(\varphi)}$$

The capture condition for the turn depends on both the turn waypoint's turn type ("Begin Turn At," "End Turn At," or "Inside Turn") and the turn type of the following turn waypoint. The possible combinations of turn waypoints and the resultant capture condition for the first turn are defined in Table 4.2.2.1.2-2.

#### Constant Course

As described above, the aircraft's lateral path (including constant course segments) is estimated geometrically in three dimensions and is not numerically integrated. The predicted time at any point along the path is calculated as part of the vertical profile segments.

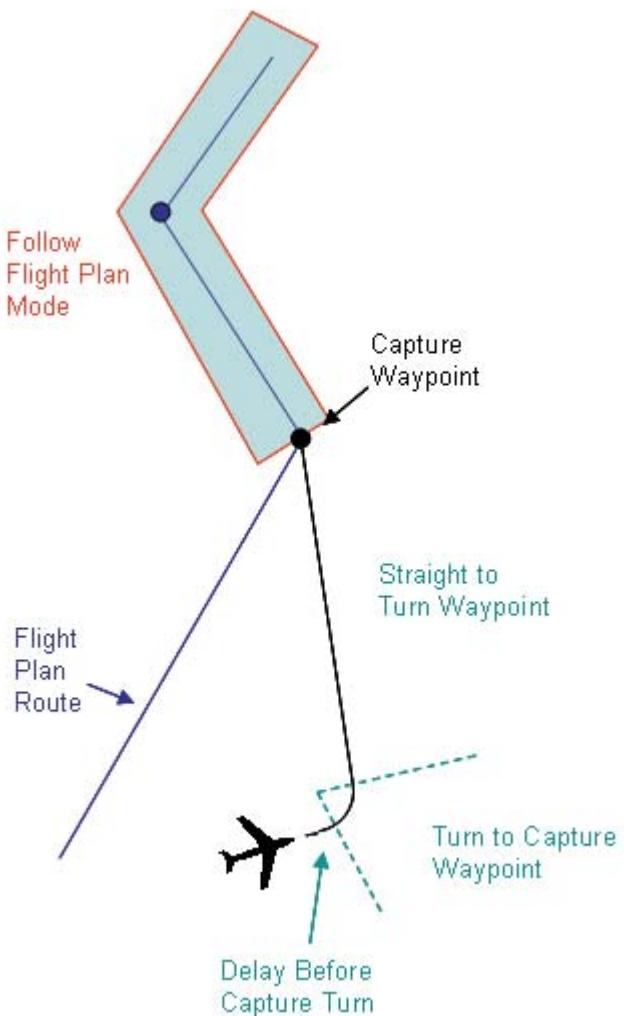
A constant course segment is created as a straight constant true course, 2D path from one position to another. The initial position is either the aircraft initial condition or the end of a turn. The possible capture condition positions are defined for the various component modes in Table 4.2.2.1.2-2.

##### 4.2.2.1.1. Waypoint Capture Mode

Table 4.2.2.1.3-1 describes the three sub-modes of the Waypoint Capture mode, including the switching conditions between them. Figure 4.2.2.1.3-1 graphically illustrates the combination of these sub- and component modes. Note that in the figure, only the case for capturing an "Inside Turn" waypoint has been illustrated, even though the capture waypoint can be any one of the three types of turn types. For an illustration of the other types, see Figure 4.2.2.1.2-1 (the turn to capture the capture waypoint is the equivalent of a "Begin Turn At" turn waypoint).

Sub-Mode	Component Modes	Applicable Cases	Capture Condition	Model	Next Sub-/Component Mode
Delay Before Capture Turn	N/A	All	Delay Time	Constant Course	Turn to Capture Waypoint
Turn to Capture Waypoint	Turn to Capture Waypoint Position	Initial Track degrees off direct to waypoint	Course to Capture Waypoint	Constant Radius Turn	Straight to Turn Waypoint
Straight to Turn Waypoint	Straight to “Inside Turn” Waypoint	Next Turn Waypoint is “Inside Turn”	Beginning of Turn at Next Waypoint	Constant Course	Turn
	Straight to “Begin Turn At” Turn Waypoint	Next Turn Waypoint is “Begin Turn At”	Position of Next turn Waypoint		
	Straight to “End Turn At” Turn Waypoint	Next Turn Waypoint is “End Turn At”	Beginning of Turn at Next Waypoint		

Table 4.2.2.1.3-1 Sub- and Component Modes of Waypoint Capture Mode



**Figure 4.2.2.1.3-1 Illustration of Combined Waypoint Capture Sub- and Component Modes**

#### Waypoint Capture Models

##### Constant Radius Turn

This is the same component mode as discussed under “Follow Flight Plan.”

##### Constant Course

This is the same component mode as discussed under “Follow Flight Plan.” The only exception is the addition of a new “time” capture condition. In this situation, the course is maintained for an input number of seconds. The end of this segment then becomes the initiation of a (Begin Turn At) turn.

#### 4.2.2.1.1. Path Stretch Mode

Table 4.2.2.1.4-1 describes the two sub-modes of the Path Stretch mode, including the switching conditions between them. Figure 4.2.2.1.4-1 graphically illustrates the combination of these sub- and component modes.

Sub-Mode	Component Modes	Applicable Cases	Capture Condition	Model	Next Sub-/Component Mode
<b>Capture Heading</b>	N/A	Input Capture Heading Available	Input Heading	Constant Radius Turn	Delay Before Capture Turn
<b>Delay Before Capture Turn</b>	N/A	All	Delay Time	Constant Course	Turn to Capture Waypoint

**Table 4.2.2.1.4-1 Sub- and Component Modes of Path Stretch Mode**

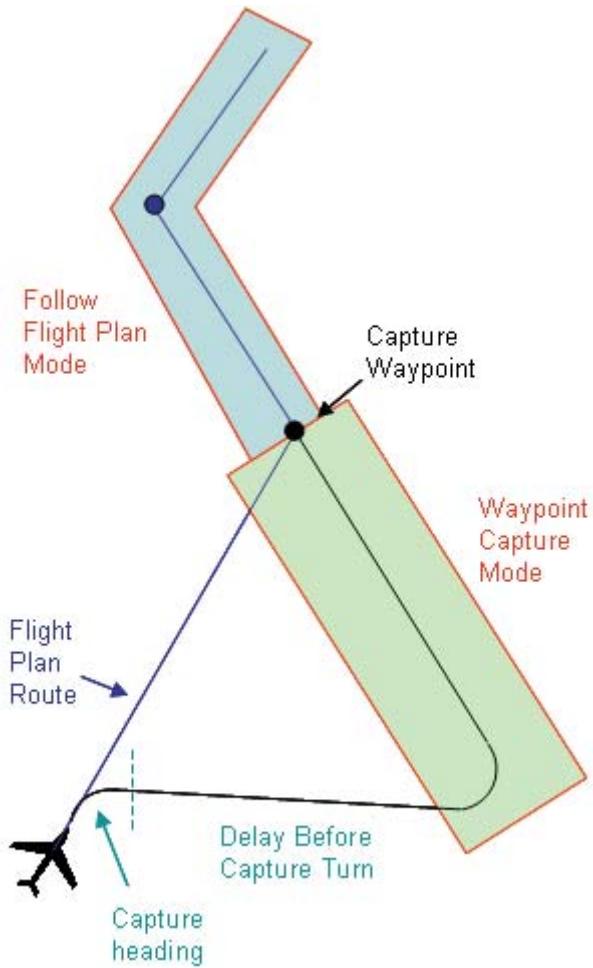
#### Path Stretch Models

##### Constant Radius Turn

This is the same component mode as discussed under “Follow Flight Plan” with the additional capture condition of a defined input course direction.

##### Constant Course

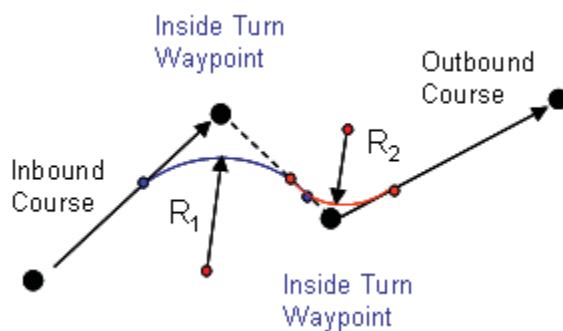
This is the same component mode as discussed under “Waypoint Capture.” It should be noted that the time required to perform the Capture Heading counts towards the total time delay required before waypoint capture.



**Figure 4.2.2.1.4-1 Illustration of Combined Path Stretch Sub- and Component Modes**

#### 4.2.2.1.1. Overlapping Adjacent Turns

After all of the turn radii are estimated from the ground speed estimations, each adjacent pair of turns is compared to determine whether the end of the first turn would overlap the beginning of the second turn (see Figure 4.2.2.1.5-1 for an example between two “Inside Turn” waypoints).



**Figure 4.2.2.1.5-1 Example Turn Overlap Situation between Two “Inside Turn” Waypoints**

If the end point of turn 1 is predicted to overlap the start point of turn 2, the two turn radii are reduced to enable both turns to be completed without overlapping. The two turn radii are set to:

$$R_1 = R_2 = \frac{0.9 * d}{\tan\left(\frac{\theta_1}{2}\right) + \tan\left(\frac{\theta_2}{2}\right)}$$

where

$R_1$  = turn radius of the first turn

$R_2$  = turn radius of the second turn

$d$  = (distance from first turn waypoint to original end of first turn) + (distance from second turn waypoint to original start of second turn)

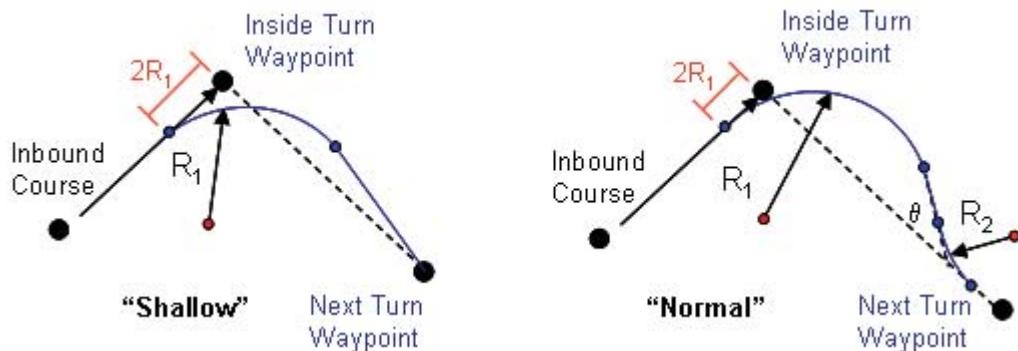
$\theta_1$  = turn angle of the first turn

$\theta_2$  = turn angle of the first turn

For “Inside Turn” waypoints, a second pass at reducing the turn radius is performed. In this case, each turn is evaluated independently and if the path distance for the turn end point is beyond the path distance of the start of the next turn (which was calculated previously), then the current turn’s turn radius is reduced by an amount to enable the turn end point to precede the next turn’s start point by 0.01 nmi. If this is not possible, a trajectory failure occurs.

#### 4.2.2.1.2. Handling “Too Large” Inside Turns

If an “Inside Turn” waypoint requires more than a  $127^{11}$  degree turn, it is considered too large for normal pilot procedures and a turn overshoot is predicted. There are two types of turn overshoots that can be created (see Figure 4.2.2.1.6-1): a “shallow” overshoot or a “normal” overshoot.



**Figure 4.2.2.1.6-1: “Shallow” Versus “Normal” Turn Overshoots**

<sup>11</sup> Actual check is to see if the start/end points of the turn are greater than twice the turn radius from the turn waypoint along the inbound/outbound course.

In both cases, the turn is initiated at a distance of  $2*R_1$  from the “Inside Turn” waypoint. A shallow overshoot does not attempt to reconnect to the original path between the “Inside Turn” waypoint and the next turn waypoint, but proceeds directly to the next turn waypoint. A normal overshoot attempts to transition back to the original path at an intercept angle ( $\theta$ ) of 30 degrees. For a normal overshoot, the turn radius  $R_2$  when reconnecting to the path can be different from the original turn radius due to the differences in course. A shallow overshoot is used in place of a normal overshoot when the reconnect point of a normal overshoot would be past the next turn waypoint.

#### *4.2.2.1.3. Priority Mode*

The Priority Mode is equivalent to a Waypoint Capture Mode where a Pseudo-Fix generated along the direct path from the aircraft’s initial position to the airport (described in Section 4.1.1.6) is automatically assigned as the capture waypoint.

#### *4.2.2.2. Vertical/Speed Segment Definitions*

For each of the eight profiles described in Table 4.1.2.3-2, the order and direction for integrating required vertical/speed modes is defined as shown in Table 4.2.2.2-1.

Profile	Mode	Integration Direction	Mode Switch/End Criteria
Climb Only	Climb	Forward	End of Lateral Path
Cruise Only	Cruise	Forward & Backward*	End of Lateral Path*
Descent Only	Descent	Forward & Backward*	End of Lateral Path*
Climb Then Cruise	Climb Cruise	Forward Forward	Cruise Altitude End of Lateral Path
Step Then Cruise	Step Descent Cruise	Forward Forward	Cruise Altitude End of Lateral Path
Climb, Cruise, Then Descent	Descent	Backward	Cruise Altitude and Cruise Speed
	Climb Cruise	Forward Forward	Cruise Altitude Beginning of Descent
Cruise Then Descent	Descent	Backward	Cruise Altitude and Cruise Speed
	Cruise	Forward	Beginning of Descent
Step, Cruise, then Descent	Descent	Backward	Cruise Altitude and Cruise Speed
	Step Descent Cruise	Forward Forward	Cruise Altitude Beginning of Descent

\* The use of forward and backward integration is defined at the sub-mode/component mode level.

**Table 4.2.2.2-1 Vertical/Speed Mode Order, Integration Direction, and Mode Switch Criteria**

For the four vertical/speed modes defined in Section 4.1.2.3, detailed definitions of sub-mode and component mode switching, as well as the vertical/speed segment definitions are provided below.

#### 4.2.2.2.1. *Kinetic Equations of Motion*

The basic equations of motion used for all of the kinetic vertical segment models (described below) are based on a point-mass model of the aircraft motion. The CTAS En Route TP makes four theoretical assumptions to simplify the point mass equations of motion:

1. A small angle assumption for the angle of attack and flight path angle
2. A small angle assumption for the crab angle (angle between the ground speed and true airspeed)
3. Turns have a constant turn radius
4. The partial derivative of the wind with respect to x and y is assumed to be zero and there is no vertical component to the wind

Given these assumptions, the equations of motion are:

$$\frac{ds}{dt} = V_g = U_w \cos(\delta_G - \delta_w) + V_T \cos(\text{Arc sin}(\frac{U_w \sin(\delta_G - \delta_w)}{V_T})) \quad (1)$$

$$\frac{dh}{dt} = \gamma_a V_T = \gamma_i V_G \quad (2)$$

$$\frac{dv_T}{dt} = \frac{T-D}{m} - g\gamma_a - \gamma_a V_T \frac{dU_w}{dh} \quad (3)$$

where

$s$  = horizontal path length

$t$  = time

$V_G$  = ground speed

$U_w$  = wind speed

$\delta_G$  = direction of ground speed (clockwise from true north)

$\delta_w$  = direction of wind speed (clockwise from true north)

$V_T$  = true airspeed

$h$  = geometric altitude

$\gamma_a$  = aerodynamic flight path angle

$\gamma_i$  = inertial flight path angle

$T$  = thrust

$D$  = drag

$m$  = mass

$g$  = acceleration of gravity

Each vertical segment model that requires kinetic equations of motion uses some form of these equations (modified by other known information for that segment). Wind speed and direction are looked up within the atmospheric model data. Thrust and drag data are lookup up within the aircraft model data.

For transitions to/from level flight, an instantaneous change in inertial flight path angle is assumed.

#### 4.2.2.2.1. Climb Mode

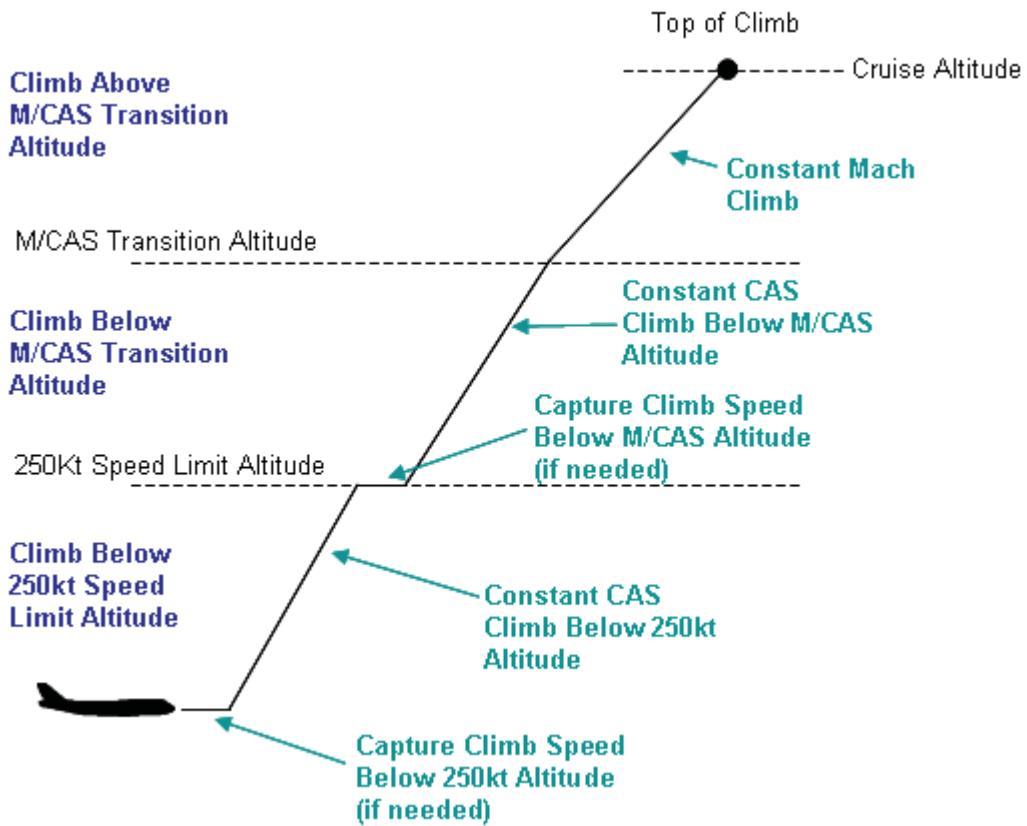
Table 4.2.2.2.2.-1 describes the three sub-modes of the Climb mode, including the switching conditions between them. Figure 4.2.2.2.2-1 graphically illustrates the possible combination of these sub- and component modes.

All three sub-modes for the Climb Mode are forward integrated. The initial condition altitude defines the first sub-mode and the initial condition CAS and desired climb CAS define the first component

<b>Sub-Mode</b>	<b>Component Modes</b>	<b>Applicable Cases</b>	<b>Capture Condition</b>	<b>Model</b>	<b>Next Sub-/Component Mode</b>
<b>Climb Below 250kt Speed Limit Altitude</b>	<b>Capture Climb Speed Below 250kt Altitude</b>	<b>Initial Altitude &lt; 250kt Speed Limit Alt; Initial CAS &lt; 250 kts; Climb CAS &gt; 250 kts</b> <b>Initial Altitude &lt; 250kt Speed Limit Alt; Initial CAS &lt; 250 kts; Climb CAS &lt; 250 kts</b>	<b>250 kts</b>	<b>Max Cruise Thrust; Constant Altitude</b>	<b>Constant CAS Climb Below 250kt Altitude</b>
			<b>Climb CAS</b>	<b>No Acceleration Modeled</b>	<b>Constant CAS Climb Below 250kt Altitude</b>
	<b>Constant CAS Climb Below 250kt Altitude</b>	<b>Initial Altitude &lt; 250kt Speed Limit Alt; Initial CAS = min(Climb CAS, 250 kts); Cruise Altitude &gt; 250kt Speed Limit Alt</b> <b>Initial Altitude &lt; 250kt Speed Limit Alt; Initial CAS = min(Climb CAS, 250 kts); Cruise Altitude &lt;= 250kt Speed Limit Alt</b>	<b>250kt Speed Limit Alt</b>	<b>Max Climb Thrust; Constant CAS</b>	<b>Climb Below M/CAS Transition Altitude</b>
			<b>Cruise Altitude</b>	<b>Max Climb Thrust; Constant CAS</b>	<b>None</b>

<b>Climb Below M/CAS Transition Altitude</b>	<b>Capture Climb Speed Below M/CAS Altitude</b>	<b>250kt Speed Limit Alt &lt; Initial Altitude &lt; M/CAS Transition Altitude; Initial CAS &lt; Climb CAS;</b>	<b>Climb CAS</b>	<b>Max Cruise Thrust; Constant Altitude</b>	<b>Constant CAS Climb Below M/CAS Altitude</b>
	<b>Constant CAS Climb Below M/CAS Altitude</b>	<b>250kt Speed Limit Alt &lt; Initial Altitude &lt; M/CAS Transition Altitude; Initial CAS &gt;= Climb CAS; Cruise Altitude &gt; M/CAS Transition Altitude</b>	<b>M/CAS Transition Altitude</b>	<b>Max Climb Thrust; Constant CAS</b>	<b>Climb Above M/CAS Transition Altitude</b>
		<b>250kt Speed Limit Alt &lt; Initial Altitude &lt; M/CAS Transition Altitude; Initial CAS &gt;= Climb CAS; Cruise Altitude &lt;= M/CAS Transition Altitude</b>	<b>Cruise Altitude</b>	<b>Max Climb Thrust; Constant CAS</b>	<b>None</b>
<b>Climb Above M/CAS Transition Altitude</b>	<b>Constant Mach Climb</b>	<b>Initial Altitude &gt;= M/CAS Transition Altitude</b>	<b>Cruise Altitude</b>	<b>Max Climb Thrust; Constant Mach</b>	<b>None</b>

**Table 4.2.2.2-1 Sub- and Component Modes of Climb Mode**



**Figure 4.2.2.2-1: Illustration of Combined Climb Sub- and Component Modes**

### Climb Models

#### Max Cruise Thrust & Constant Altitude

This model uses the kinetic equations of motion. In this model, Equation (2) reduces to

$$\frac{dh}{dt} = 0$$

and the thrust ( $T$ ) is looked up from within the aircraft model's max cruise thrust data.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target CAS value.

#### Max Climb Thrust & Constant CAS

This model uses the kinetic equations of motion. From the constant CAS value, the value of  $V_T$  can be determined at each new altitude. The thrust ( $T$ ) is looked up from within the aircraft model's max cruise thrust data.

The CTAS En Route TP uses a fixed time step of 60 seconds during integration and the capture condition is a target altitude value.

#### Max Climb Thrust & Constant Mach

This model uses the kinetic equations of motion. From the constant Mach value, the value of  $V_T$  can be determined at each new altitude. The thrust (T) is looked up from within the aircraft model's max cruise thrust data.

The CTAS En Route TP uses a fixed time step of 60 seconds during integration and the capture condition is a target altitude value.

#### Error Cases

If any sub-mode fails to capture a desired altitude, the CTAS TP throws an error.

##### *4.2.2.2.1. Cruise Mode*

Table 4.2.2.2.3-1 describes the three sub-modes of the Cruise mode, including the switching conditions between them. Figure 4.2.2.2.3-1 graphically illustrates the possible combination of these sub- and component modes.

It should be noted that the Capture Target Speed sub-mode is only used for aircraft that are only cruising at level flight for their entire trajectory (i.e., Overflight Aircraft). In this case, the order and direction for integrating required sub-modes is as described in Table 4.2.2.2.3-2. For non-Overflight Aircraft, the two remaining sub-modes are both forward integrated. In these cases, the initial condition CAS defines the first sub-mode and the initial condition CAS and desired cruise CAS define the first component mode, as described in the applicable cases column of the Table 4.2.2.2.3-1.

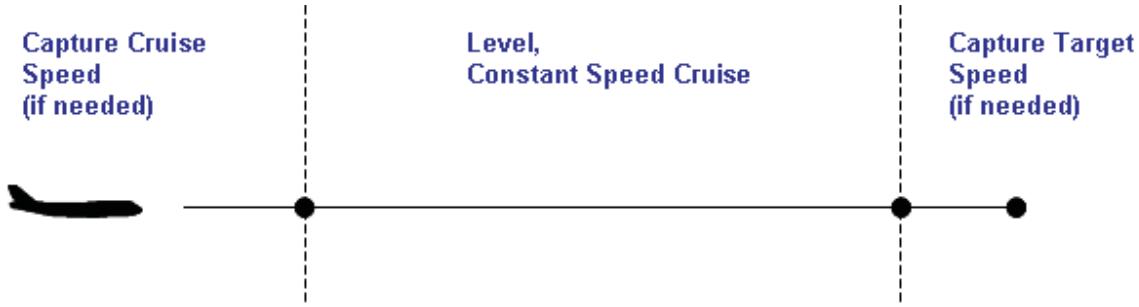
Sub-Mode	Component Modes	Applicable Cases	Capture Condition	Model	Next Sub-/Component Mode
Capture Cruise Speed	Accelerate to Cruise Speed	Initial CAS < Cruise CAS	Cruise M/CAS	Max Cruise Thrust; Constant Altitude	Level, Constant Speed Cruise
	Decelerate to Cruise Speed	Initial CAS > Cruise CAS		Idle Thrust; Constant Altitude	
Level, Constant Speed Cruise	N/A	Initial Mach = Cruise Mach; Cruise Altitude >= M/CAS Transition Altitude	Path Distance**	Constant Mach; Constant Altitude	None
		Initial CAS = Cruise CAS; Cruise Altitude < M/CAS Transition Altitude		Constant CAS; Constant Altitude	
		Target CAS > Cruise CAS	Cruise CAS	Max Cruise Thrust; Constant Altitude	
		Decelerate to Target Speed		Idle Thrust; Constant Altitude	
Capture Target Speed*	Accelerate to Target Speed	Target CAS > Cruise CAS	Cruise CAS	Max Cruise Thrust; Constant Altitude	Capture Cruise Speed***

\* The Capture Target Speed Sub-mode is only applicable for aircraft that only have a cruise segment (Overflight).

\*\* The Level, Constant Speed Cruise segment captures an appropriate path location. These include: start of the descent mode (backward integrated before hand), end of the lateral path (if no follow on mode), or start of the target speed change (backward integrated before hand).

\*\*\* Next sub-mode is Level, Constant Speed Cruise if Initial Mach/CAS = Cruise Mach/CAS.

**Table 4.2.2.2.3-1 Sub- and Component Modes of Cruise Mode**



**Figure 4.2.2.2.3-1: Illustration of Combined Climb Sub- and Component Modes**

Sub-Mode	Applicable Cases	Integration Direction	Mode Switch/End Criteria
Capture Target Speed	Target CAS <> Cruise CAS	Backward	Cruise CAS
Capture Cruise Speed	Initial CAS <> Cruise CAS	Forward	Cruise CAS
Level, Constant Speed Cruise	Initial CAS = Cruise CAS	Forward	Begin Speed Change to Target CAS

**Table 4.2.2.2.3-2 Sub-Mode Order, Integration Direction, and Mode Switch Criteria for Cruise Mode (Overflight Aircraft).**

#### Cruise Models

##### Max Cruise Thrust & Constant Altitude

This model uses the kinetic equations of motion. In this model, Equation (2) reduces to

$$\frac{dh}{dt} = 0$$

and the thrust (T) is looked up from within the aircraft model's max cruise thrust data.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target CAS value.

##### Idle Thrust & Constant Altitude

This model uses the kinetic equations of motion. In this model, Equation (2) reduces to

$$\frac{dh}{dt} = 0$$

and the thrust (T) is looked up from within the aircraft model's idle thrust data.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target CAS value.

#### Constant Mach & Constant Altitude

This model uses the kinetic equations of motion. In this model, Equation (2) reduces to

$$\frac{dh}{dt} = 0$$

From the constant Mach value, the value of  $V_T$  can be determined at each new timestep.

The CTAS En Route TP uses a fixed time step of 300 seconds during integration. The capture condition is a target known path location (either the start of a Descent Mode, the end of the lateral path, or the start of speed change).

#### Constant CAS & Constant Altitude

This model uses the kinetic equations of motion. In this model, Equation (2) reduces to

$$\frac{dh}{dt} = 0$$

From the constant CAS value, the value of  $V_T$  can be determined at each new timestep.

The CTAS En Route TP uses a fixed time step of 300 seconds during integration. The capture condition is a target known path location (either the start of a Descent Mode, the end of the lateral path, or the start of speed change).

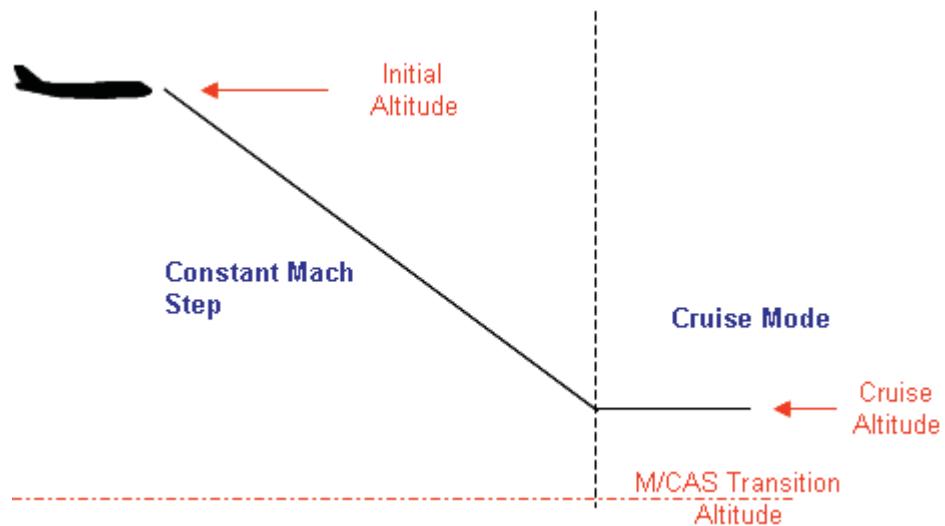
##### 4.2.2.2.1. Step Descent Mode

Table 4.2.2.2.4-1 describes the three sub-modes of the Step Descent mode, including the switching conditions between them. Figures 4.2.2.2.4-1 through 4.2.2.2.4-4 graphically illustrate the possible combination of these sub- and component modes.

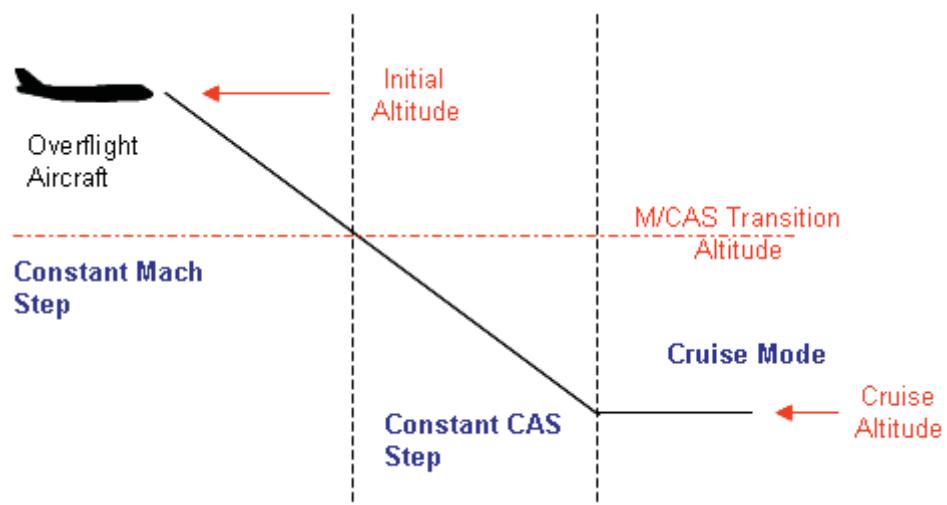
All three sub-modes for the Step Descent Mode are forward integrated. The initial condition and cruise altitudes define the first sub-mode and component mode, as described in the applicable cases column of the Table.

Sub-Mode	Component Modes	Applicable Cases	Capture Condition	Model	Next Sub-/Component Mode
Constant Mach Step	N/A	Initial Alt > MCTA; Cruise Alt > MCTA;  Initial Alt > Cruise Alt; Overflight Aircraft Initial Alt > MCTA; Cruise Alt < MCTA; Overflight Aircraft  Initial Alt > Cruise Alt > Final Alt; Initial CAS < Cruise CAS (or 310 kts) && Initial Mach < cruise Mach; Jet Aircraft  Initial Alt > Cruise Alt > Final Alt; Initial CAS < Cruise CAS (or 310 kts) && Initial Mach >= cruise Mach; Jet Aircraft	Cruise Altitude  Mach/CAS Transition Altitude Cruise Altitude	Constant Mach; Constant Flight Path Angle	None Constant CAS Step None
Constant CAS Step	N/A	Initial Alt > Cruise Alt; Overflight Aircraft Initial Alt > Cruise Alt > Final Alt; Initial CAS < Cruise CAS (or 310 kts) && Initial Mach at cruise alt >= cruise Mach; Jet Aircraft Initial Alt > Cruise Alt > Final Alt; Turboprop or Prop Aircraft	Cruise Altitude	Constant CAS; Constant Flight Path Angle	None
Idle CAS Step	N/A	Initial Alt > Cruise Alt > Final Alt; Initial CAS >= Cruise CAS (or 310 kts); Jet Aircraft	Cruise Altitude	Idle Thrust; Constant CAS	None

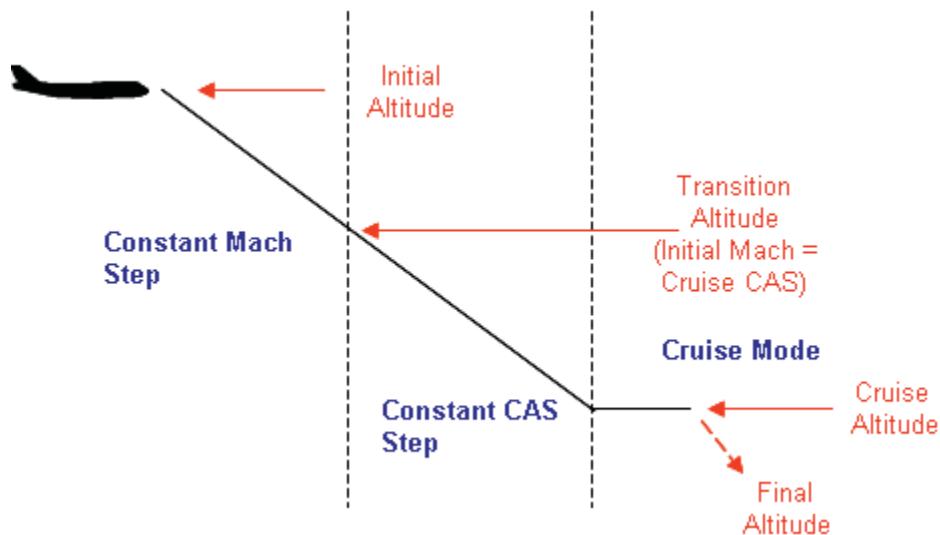
Table 4.2.2.4-1 Sub- and Component Modes of Step Descent Mode



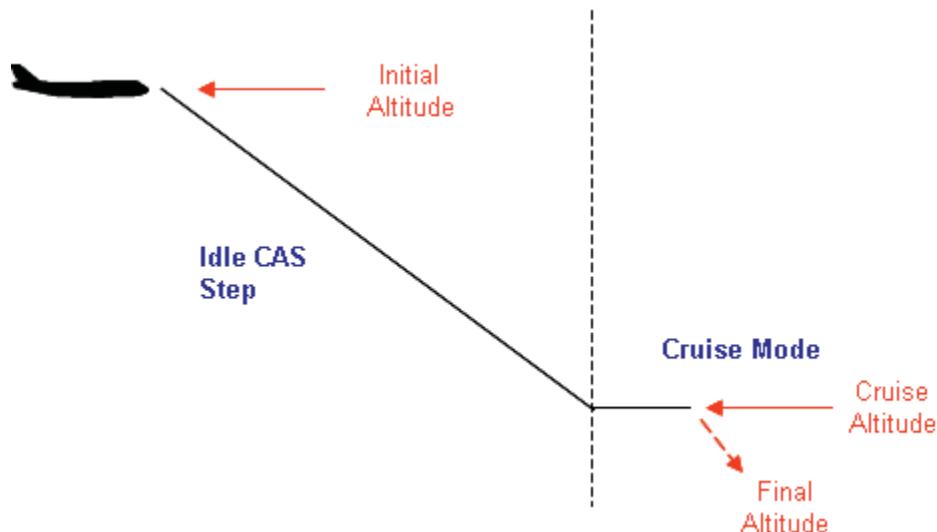
**Figure 4.2.2.2.4-1: Illustration of Combined Step Descent Sub- and Component Modes: Constant Mach Step**



**Figure 4.2.2.2.4-2: Illustration of Combined Step Descent Sub- and Component Modes: Constant Mach and Constant CAS Step (Overflight Aircraft)**



**Figure 4.2.2.2.4-3: Illustration of Combined Step Descent Sub- and Component Modes: Constant Mach and Constant CAS Step (Arrival Aircraft)**



**Figure 4.2.2.2.4-4: Illustration of Combined Step Descent Sub- and Component Modes: Idle CAS Step (Jet Arrival Aircraft)**

### Step Descent Models

#### Constant Mach & Constant Flight Path Angle

This model uses the kinetic equations of motion. From the constant inertial flight path angle (set to -3 degrees), the vertical rate ( $dh/dt$ ) becomes just a function of  $V_G$ . From the constant Mach value, the value of  $V_T$  can be determined at each new altitude.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target altitude or CAS value.

#### Constant CAS & Constant Flight Path Angle

This model uses the kinetic equations of motion. From the constant inertial flight path angle (set to -3 degrees), the vertical rate ( $dh/dt$ ) becomes just a function of  $V_G$ . From the constant CAS value, the value of  $V_T$  can be determined at each new altitude.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target altitude value.

#### Idle Thrust & Constant CAS

This model uses the kinetic equations of motion. The thrust (T) is looked up from within the aircraft model's idle thrust data. From the constant CAS value, the value of  $V_T$  can be determined at each new altitude.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target altitude value.

##### 4.2.2.2.1. Descent Mode

There are two main sub-modes for the Descent Mode: Fixed TOD Descent and Predicted TOD Descent. The Fixed TOD Descent sub-mode is used primarily when the aircraft is already in a descent. In this case, the aircraft only has one mode and it is a Descent Mode. The Predicted TOD Descent sub-mode is used in conjunction with other modes (at a minimum a Cruise Mode) to create more complex combined modes.

Table 4.2.2.2.5-1 describes the order and direction for integrating required Fixed TOD Descent sub-modes and Table 4.2.2.2.5-2 describes these three sub-modes, including the switching conditions between them. Figure 4.2.2.2.5-1 graphically illustrates the possible combination of these sub- and component modes.

Sub-Mode	Applicable Cases	Integration Direction	Mode Switch/End Criteria
Capture Crossing	Crossing CAS <> Descent CAS	Backward	Descent CAS
Restriction CAS			
Capture	Initial CAS <> Descent CAS	Forward	Descent CAS
Descent CAS	Descent CAS		
Capture Bottom of Descent	Initial CAS = Descent CAS	Forward	Bottom of Descent (Path Distance)

**Table 4.2.2.2.5-1 Sub-Mode Order, Integration Direction, and Mode Switch Criteria for Fixed TOD Descent Sub-Mode.**

Sub-Mode	Component Modes	Applicable Cases	Capture Condition	Model	Next Sub-/Component

<b>Capture Descent CAS</b>	Accelerate to Descent CAS	Initial CAS < Descent CAS	Descent CAS	Max Cruise Thrust; Constant Flight Path Angle	Mode Capture Bottom of Descent
	Decelerate to Descent CAS	Initial CAS > Descent CAS	Descent CAS	Idle Thrust; Constant Altitude	Capture Bottom of Descent
<b>Capture Bottom of Descent</b>	N/A	Initial CAS = Descent CAS	Bottom of Descent (Path Distance)	Constant CAS; Constant Flight Path Angle	None
<b>Capture Crossing Restriction CAS</b>	Accelerate to Crossing CAS	Descent CAS < Crossing CAS	Descent CAS	Max Cruise Thrust; Constant Altitude	Capture Descent CAS
	Decelerate to Crossing CAS	Descent CAS > Crossing CAS	Descent CAS	Idle Thrust; Constant Altitude	Capture Descent CAS

Table 4.2.2.5-2 Sub- and Component Modes of Fixed TOD Descent Mode

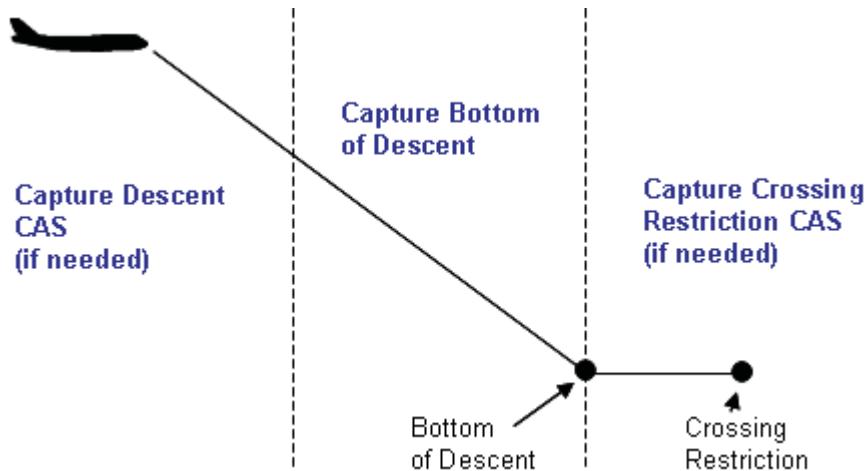


Figure 4.2.2.5-1: Illustration of Combined Fixed TOD Descent Sub- and Component Modes

Tables 4.2.2.5-3 through 4.2.2.5-6 describe the allowed order and direction for integrating required Predicted TOD Descent sub-modes and Table 4.2.2.5-7 describes all six of these sub-modes, including the switching conditions between them. Figures 4.2.2.5-2 through 4.2.2.5-5 graphically illustrate the possible combinations of these sub- and component modes.

The logic for determining the correct combination of the Predicted TOD Descent sub- and component modes is based on the relationship between the aircraft's cruise altitude, final (crossing restriction) altitude, M/CAS Transition Altitude (see Section 4.1.3.9.1), and Descent Transition Altitude (see Section 4.1.3.9.2).

Table 4.2.2.2.5-3 and Figure 4.2.2.2.5-2 show the case when the cruise altitude is above the Descent Transition Altitude and the final altitude is below the M/CAS Transition Altitude and the Descent Transition Altitude.<sup>12</sup> In this case, a transition from the Cruise Mach is used (if necessary) to capture the Descent Mach, and then the Descent Mach is held constant through the beginning of the descent to transition to the desired Descent CAS.

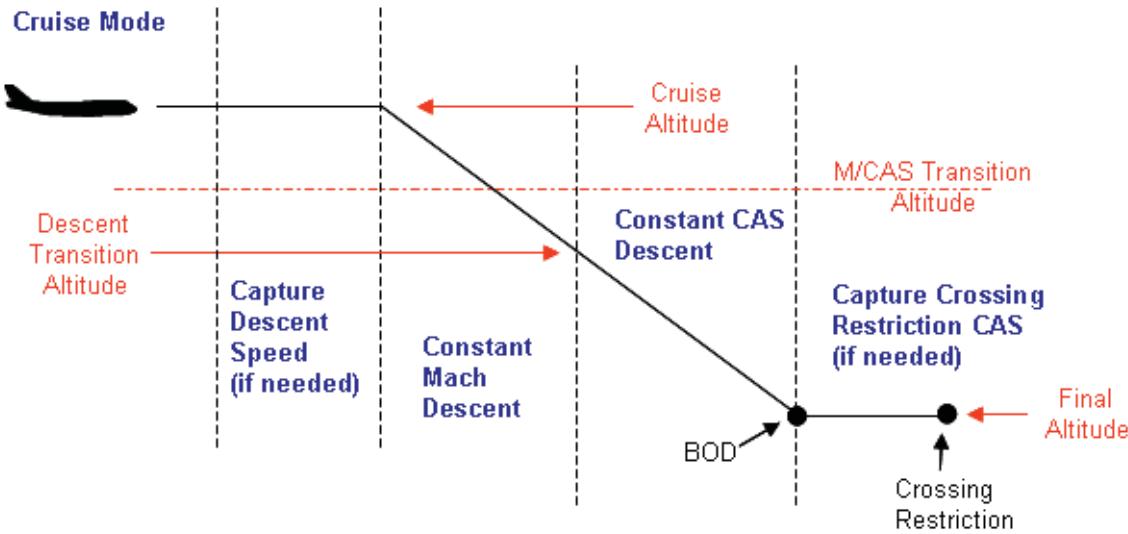
Sub-Mode	Applicable Cases	Integration Direction	Mode Switch/End Criteria
Capture Crossing Restriction CAS	<b>Crossing CAS &lt;&gt; Descent CAS</b>	<b>Backward</b>	<b>Descent CAS</b>
Constant CAS Descent	<b>Cruise Alt &gt;= DTA;</b> <b>Final Alt &lt; MCTA;</b> <b>Final Alt &lt;= DTA</b>	<b>Backward</b>	<b>Descent Mach</b>
Constant Mach Descent	<b>Cruise Alt &gt;= Trans Alt</b>	<b>Backward</b>	<b>Cruise Altitude</b>
Capture Descent Speed	<b>Descent Mach &lt;&gt; Cruise Mach</b>	<b>Backward</b>	<b>Cruise Mach</b>

DTA = Descent Transition Altitude; MCTA = M/CAS Transition Altitude

**Table 4.2.2.2.5-3 Sub-Mode Order, Integration Direction, and Mode Switch Criteria for Predicted TOD Descent Sub-Mode: Constant M and Constant CAS.**

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<sup>12</sup> The code actually checks to see if the Mach at the BOD (i.e., the Mach associated with the Descent CAS at the final altitude) is less than or equal to the Descent Mach, which implies the final altitude is at or below the Descent Transition Altitude.



**Figure 4.2.2.2.5-2: Illustration of Combined Predicted TOD Descent Sub- and Component Modes: Constant M and Constant CAS.**

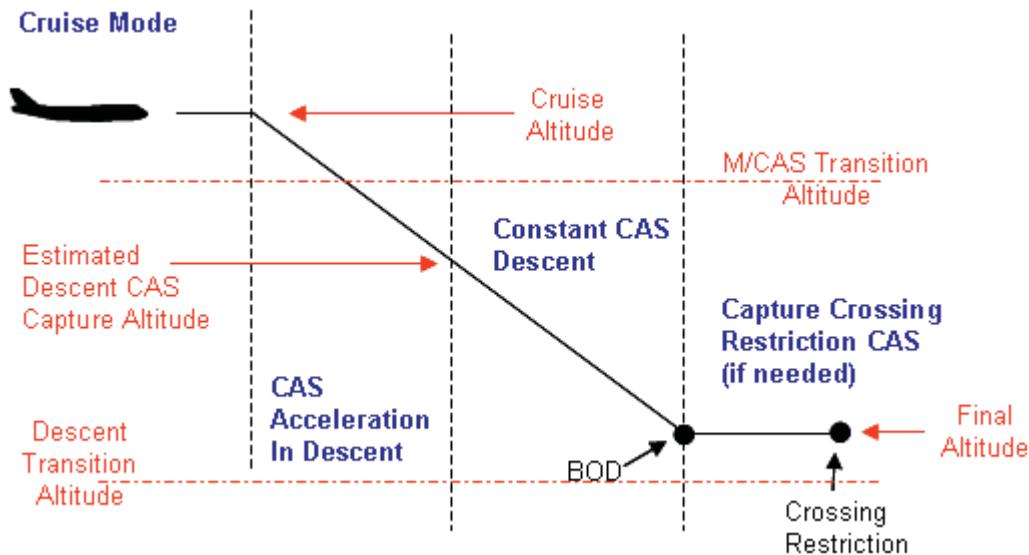
Table 4.2.2.2.5-4 and Figure 4.2.2.2.5-3 show the case when the cruise altitude is above the Descent Transition Altitude and the final altitude is below the M/CAS Transition Altitude but above the Descent Transition Altitude.<sup>13</sup> In this case, using the Descent Mach to transition to the Descent CAS is not sufficient to achieve the descent CAS prior to the final altitude. The procedure used in this case is to accelerate (in both Mach and CAS) in the initial part of the descent until capturing the descent CAS.

Sub-Mode	Applicable Cases	Integration Direction	Mode Switch/End Criteria
Capture Crossing Restriction CAS	Crossing CAS <>> Descent CAS	Backward	Descent CAS
Constant CAS Descent	Cruise Alt $\geq$ MCTA & DTA; Final Alt < MCTA; Final Alt > DTA	Backward	Estimated Descent CAS Capture Altitude
CAS Acceleration in Descent	Mach at Final Alt > Descent Mach	Backward	Cruise Altitude

DTA = Descent Transition Altitude; MCTA = M/CAS Transition Altitude

**Table 4.2.2.2.5-4 Sub-Mode Order, Integration Direction, and Mode Switch Criteria for Predicted TOD Descent Sub-Mode: CAS Acceleration in Descent.**

<sup>13</sup> The code actually checks to see if the Mach at the BOD (i.e., the Mach associated with the Descent CAS at the final altitude) is greater than the Descent Mach, which implies the final altitude is above the Descent Transition Altitude.



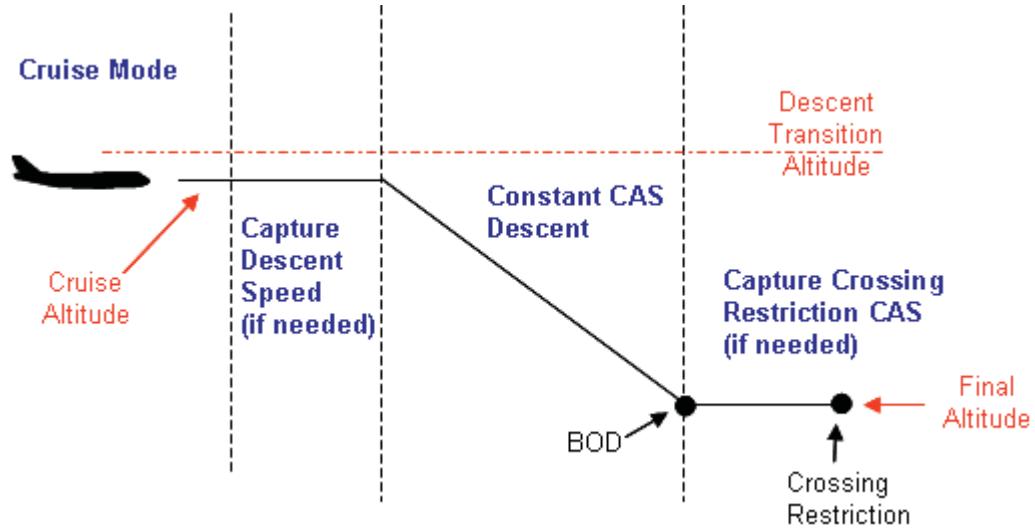
**Figure 4.2.2.2.5-3: Illustration of Combined Predicted TOD Descent Sub- and Component Modes: CAS Acceleration in Descent.**

Table 4.2.2.2.5-5 and Figure 4.2.2.2.5-4 show the case when the cruise altitude is below the Descent Transition Altitude and the final altitude is below the M/CAS Transition Altitude. In this case, a transition from the Cruise CAS to the Descent CAS at the cruise altitude is performed (if required), followed by a constant CAS descent at the Descent CAS.

Sub-Mode	Applicable Cases	Integration Direction	Mode Switch/End Criteria
Capture Crossing Restriction CAS	Crossing CAS <> Descent CAS	Backward	Descent CAS
Constant CAS Descent	Cruise Alt < DTA; Final Alt < MCTA	Backward	Cruise Altitude
Capture Descent Speed	Descent CAS <> Cruise CAS	Backward	Cruise CAS

DTA = Descent Transition Altitude; MCTA = M/CAS Transition Altitude

**Table 4.2.2.2.5-5 Sub-Mode Order, Integration Direction, and Mode Switch Criteria for Predicted TOD Descent Sub-Mode: CAS Change at Cruise Altitude.**



**Figure 4.2.2.2.5-4: Illustration of Combined Predicted TOD Descent Sub- and Component Modes: CAS Change at Cruise Altitude.**

Table 4.2.2.2.5-6 and Figure 4.2.2.2.5-5 show the case when the cruise altitude and the final altitude are above the Descent Transition Altitude.<sup>14</sup> In this case, the Descent CAS can not be achieved before the final altitude, so a Mach acceleration from the Cruise Speed is performed to achieve the crossing restriction speed at the final altitude.

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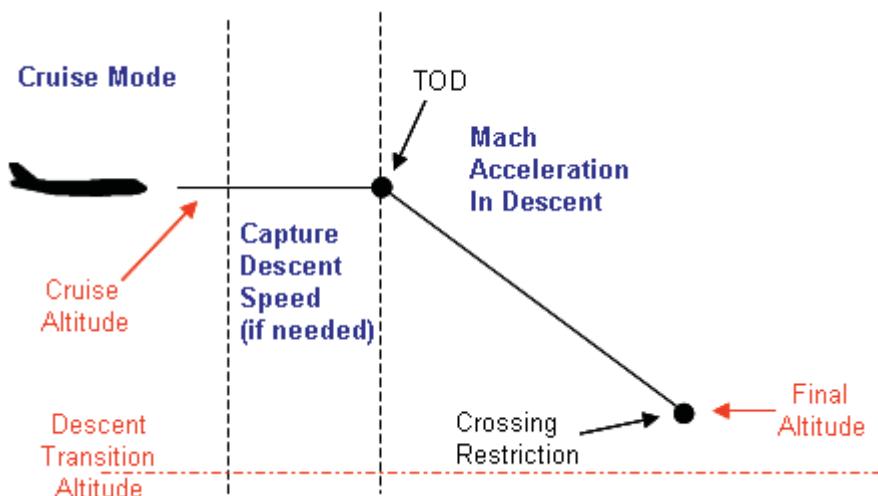
<sup>14</sup> The code actually checks to see if the Mach at the initial time step (the BOD in this case) is greater than the Descent Mach. This should imply that the final altitude is above the Descent Transition Altitude.

Sub-Mode	Component Modes	Applicable Cases	Capture Condition	Model	Next Sub-/Component Mode
Capture Descent Speed	Accelerate to Descent Speed	Descent M/CAS > Cruise M/CAS	Cruise Mach or Cruise CAS	Max Cruise Thrust; Constant Altitude	None
	Decelerate to Descent Speed	Descent M/CAS < Cruise M/CAS	Cruise Mach or Cruise CAS	Idle Thrust; Constant Altitude	None
Mach Acceleration in Descent	N/A	Cruise Alt >= DTA; Mach at end of segment > Descent Mach	Cruise Altitude	Max Cruise Thrust; Constant Vertical Speed	None
CAS Acceleration in Descent	N/A	Mach at BOD > Descent Mach	Cruise Altitude or Cruise CAS	Max Cruise Thrust; Constant Vertical Speed	None
Constant Mach Descent	N/A	Cruise Alt >= DTA; Final Alt > DTA	Cruise Altitude	Idle Thrust; Constant Mach	Capture Descent Speed
Constant CAS Descent	N/A	Cruise Alt >= DTA; Final Alt < MCTA; Final Alt <= DTA;	Descent Mach	Idle Thrust; Constant CAS	Constant Mach Descent
		Jet Aircraft Cruise Alt >= DTA; Final Alt < MCTA; Final Alt <= DTA; Turboprop or Prop Aircraft	Descent Mach	Constant CAS; Constant Flight Path Angle	Constant Mach Descent
	Estimate d	Cruise Alt >= MCTA & DTA; Final Alt < MCTA; Final Alt > DTA; Jet Aircraft	Descent CAS	Idle Thrust; Constant CAS	CAS Acceleration in Descent
		Cruise Alt >= MCTA & DTA; Final Alt < MCTA; Final Alt > DTA;	Capture Altitude	Constant CAS; Constant Flight Path	CAS Acceleration in Descent

	Turboprop or Prop Aircraft	Altitude	Angle	
	Cruise Alt < DTA; Final Alt < MCTA ; Jet Aircraft	Cruise Altitude	Idle Thrust; Constant CAS	Capture Descent Speed
	Cruise Alt < DTA; Final Alt < MCTA;	Cruise Altitude	Constant CAS; Constant Flight Path Angle	Capture Descent Speed
	Turboprop or Prop Aircraft			
Capture Crossing Restriction CAS	Accelerate to Crossing CAS	Descent CAS < Crossing CAS; Final Alt < DTA	Descent CAS	Max Cruise Thrust; Constant Altitude
	Decelerate to Crossing CAS	Descent CAS > Crossing CAS; Final Alt < DTA	Descent CAS	Idle Thrust; Constant Altitude
				Constant CAS Descent
Sub-Mode	Applicable Cases	Integration Direction	Mode Switch/End Criteria	
Mach Acceleration in Descent	Cruise Alt > DTA; Final Alt > DTA.	Backward	Cruise Altitude	
Capture Descent Speed	Mach at TOD <> Cruise Mach	Backward	Cruise Mach	

DTA = Descent Transition Altitude; MCTA = M/CAS Transition Altitude

**Table 4.2.2.2.5-6 Sub-Mode Order, Integration Direction, and Mode Switch Criteria for Predicted TOD Descent Sub-Mode: Mach Acceleration in Descent.**



**Figure 4.2.2.2.5-5: Illustration of Combined Predicted TOD Descent Sub- and Component Modes: Mach Acceleration in Descent.**

DTA = Descent Transition Altitude; MCTA = M/CAS Transition Altitude

**Table 4.2.2.2.5-4 Sub- and Component Modes of Predicted TOD Descent Mode**

Descent Models

Max Cruise Thrust & Constant Flight Path Angle

This model uses the kinetic equations of motion. From the constant inertial flight path angle (set to -3 degrees), the vertical rate ( $dh/dt$ ) becomes just a function of  $V_G$ . The thrust (T) is looked up from within the aircraft model's max cruise thrust data

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target CAS value.

Max Cruise Thrust & Constant Altitude

This model uses the kinetic equations of motion. In this model, Equation (2) reduces to

$$\frac{dh}{dt} = 0$$

and the thrust (T) is looked up from within the aircraft model's max cruise thrust data.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target CAS value.

Max Cruise Thrust & Constant Vertical Speed

This model uses the kinetic equations of motion. In this model, Equation (2) reduces to

$$\frac{dh}{dt} = 3000 \text{ fpm}$$

and the thrust (T) is looked up from within the aircraft model's max cruise thrust data.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target CAS or altitude value.

Idle Thrust & Constant Altitude

This model uses the kinetic equations of motion. In this model, Equation (2) reduces to

$$\frac{dh}{dt} = 0$$

and the thrust (T) is looked up from within the aircraft model's idle thrust data.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target CAS value.

#### Idle Thrust & Constant Mach

This model uses the kinetic equations of motion. The thrust (T) is looked up from within the aircraft model's idle thrust data. From the constant Mach value, the value of  $V_T$  can be determined at each new altitude.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target altitude value.

#### Idle Thrust & Constant CAS

This model uses the kinetic equations of motion. The thrust (T) is looked up from within the aircraft model's idle thrust data. From the constant CAS value, the value of  $V_T$  can be determined at each new altitude.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration and the capture condition is a target altitude or Mach value.

The target altitude capture condition is an estimated altitude representing the end of the CAS Acceleration in Descent Sub-Mode. This altitude is estimated as follows:

1. Estimate the initial course angle by:
  - a. Estimating the path distance of the initial condition by assuming a constant inertial flight path angle of 3 degrees from the BOD
  - b. Finding the course angle at this path distance from the horizontal path
2. Predict a descent (using the kinematic equations of motion) with:
  - a. Thrust (T) looked up from within the aircraft model's max cruise thrust data
  - b. Setting  $dh/dt = 3000$  fpm
  - c. Using a timestep of 30 seconds
  - d. Capturing the Descent CAS and the final (BOD) altitude
3. The estimated target altitude is the altitude at which the Descent CAS is predicted to be captured

#### Constant CAS & Constant Flight Path Angle

This model uses the kinetic equations of motion. From the constant inertial flight path angle, the vertical rate ( $dh/dt$ ) becomes just a function of  $V_G$ . For the Predicted TOD Descent Sub-Mode, the inertial flight path angle is set to -3 degrees. For the Fixed TOD Descent Sub-Mode, the inertial flight path angle is set to:

$$\gamma_i = \frac{h_{BOD} - h_{CAS,Capture}}{s_{BOD} - s_{CAS,Capture}}$$

where

$h_{BOD}$  = the altitude at the predicted bottom of descent

$h_{CAS,Capture}$  = the altitude at the predicted capture of the descent CAS

$s_{BOD}$  = the horizontal path length at the predicted bottom of descent

$s_{CAS,Capture}$  = the horizontal path length at the predicted capture of the descent

CAS

From the constant CAS value, the value of  $V_T$  can be determined at each new altitude.

The CTAS En Route TP uses a fixed time step of 30 seconds during integration. For the Fixed TOD Descent Sub-Mode, the capture condition is a target path distance value ( $s_{BOD}$ ). For the Predicted TOD Descent Sub-Mode, the capture condition is a Mach or altitude value.

The target altitude capture condition is an estimated altitude representing the end of the CAS Acceleration in Descent Sub-Mode. This altitude is estimated as follows:

1. Estimate the initial course angle by:
  - a. Estimating the path distance of the initial condition by assuming a constant inertial flight path angle of 3 degrees from the BOD
  - b. Finding the course angle at this path distance from the horizontal path
2. Predict a descent (using the kinematic equations of motion) with:
  - a. Thrust (T) looked up from within the aircraft model's max cruise thrust data
  - b. Setting  $dh/dt = 3000$  fpm
  - c. Using a timestep of 30 seconds
  - d. Capturing the Descent CAS and the final (BOD) altitude
3. The estimated target altitude is the altitude at which the Descent CAS is predicted to be captured

### Error Cases

Accelerate to Descent CAS – If can't capture speed before BOD distance, returns an error.

Constant CAS Descent – If fails to capture Descent Mach, throws an error.

#### *4.2.2.3. Timestep Selection*

Since the lateral path is not integrated, the timestep of the appropriate vertical segment is used as the integration timestep.

#### *4.2.2.4. Numerical Integration Approach*

The CTAS En Route TP uses a 2<sup>nd</sup> Order Runga Kutta method to integrate all vertical segment types.

### *4.2.3. Meteorological Modeling*

The CTAS En Route TP uses two different interpolation schemes with the RUC data:

- a 3D polynomial interpolation scheme when the data is within the grid, and
- a 1D linear extrapolation scheme if the data is outside of the grid.

### *3D Polynomial Scheme*

For the 3D polynomial scheme, the interpolated value at a point  $P(x, y, h)$  which is surrounded by eight grid points (see Figure 4.2.3-1) whose values are given by  $P_k(x_k, y_k, h_k)$  where  $k=0, 1, \dots, 7$ , is calculated from the formula:

$$P(x, y, h) = ((a_0 * h + a_1) * y + (a_2 * h + a_3)) * x + ((a_4 * h + a_5) * y + (a_6 * h + a_7))$$

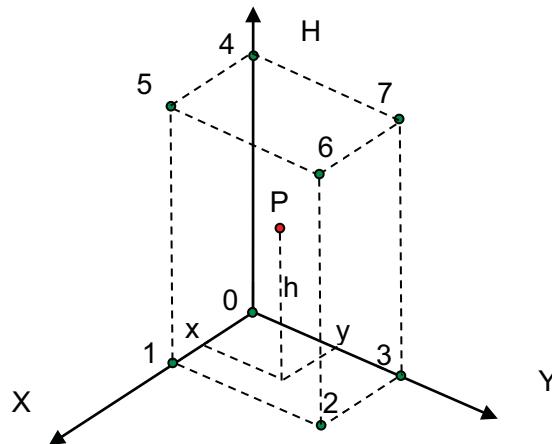
To find the eight unknown coefficients ( $a_0 \dots a_7$ ), eight equations are defined by substituting the eight known grid point values into the above equation to get:

$$P_0(x_0, y_0, h_0) = ((a_0 * h_0 + a_1) * y_0 + (a_2 * h_0 + a_3)) * x_0 + ((a_4 * h_0 + a_5) * y_0 + (a_6 * h_0 + a_7))$$

$$P_1(x_1, y_1, h_1) = ((a_0 * h_1 + a_1) * y_1 + (a_2 * h_1 + a_3)) * x_1 + ((a_4 * h_1 + a_5) * y_1 + (a_6 * h_1 + a_7))$$

:

$$P_7(x_7, y_7, h_7) = ((a_0 * h_7 + a_1) * y_7 + (a_2 * h_7 + a_3)) * x_7 + ((a_4 * h_7 + a_5) * y_7 + (a_6 * h_7 + a_7))$$



**Figure 4.2.3-1: Illustration of 3D Polynomial Interpolation**

These eight equations can be rewritten in matrix form as  $A^*a = f$ :

$$\begin{bmatrix} x_0 * y_0 * h_0 & x_0 * y_0 & x_0 * h_0 & x_0 & y_0 * h_0 & y_0 & h_0 & 1 \\ x_1 * y_1 * h_1 & x_1 * y_1 & x_1 * h_1 & x_1 & y_1 * h_1 & y_1 & h_1 & 1 \\ x_2 * y_2 * h_2 & x_2 * y_2 & x_2 * h_2 & x_2 & y_2 * h_2 & y_2 & h_2 & 1 \\ x_3 * y_3 * h_3 & x_3 * y_3 & x_3 * h_3 & x_3 & y_3 * h_3 & y_3 & h_3 & 1 \\ x_4 * y_4 * h_4 & x_4 * y_4 & x_4 * h_4 & x_4 & y_4 * h_4 & y_4 & h_4 & 1 \\ x_5 * y_5 * h_5 & x_5 * y_5 & x_5 * h_5 & x_5 & y_5 * h_5 & y_5 & h_5 & 1 \\ x_6 * y_6 * h_6 & x_6 * y_6 & x_6 * h_6 & x_6 & y_6 * h_6 & y_6 & h_6 & 1 \\ x_7 * y_7 * h_7 & x_7 * y_7 & x_7 * h_7 & x_7 & y_7 * h_7 & y_7 & h_7 & 1 \end{bmatrix} \cdot \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \\ a_7 \end{bmatrix} = \begin{bmatrix} f_0 \\ f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \\ f_7 \end{bmatrix}$$

This set of equations is solved for the coefficients ( $a_0 \dots a_7$ ) by finding the inverse of the A matrix:

$$a = A^{-1} * f$$

### *1D Linear Scheme*

For the 1D extrapolation, a value Y is calculated for a corresponding X value, given two grid points ( $x_1, y_1$ ) and ( $x_2, y_2$ ) by the formula:

$$Y = y_1 + (X - x_1) \frac{(y_2 - y_1)}{(x_2 - x_1)}$$

#### 4.2.4. Aircraft Performance Modeling

##### *4.2.4.1. Kinetic Performance Model*

When required by the vertical segment equations of motion, the CTAS En Route TP uses a kinetic aircraft performance model derived from aircraft manufacturer's performance data. This approach was chosen to enable descent trajectories, based on idle thrust descent procedures, to be comparable to the descent management approaches used by airborne flight management systems.

The CTAS aircraft model data is broken into three pieces:

1. aircraft specific modeling data
2. airframe drag modeling data
3. engine thrust modeling data

Each of the 400+ recognized FAA aircraft types are defined within the aircraft specific model data. For each of the types, Table 4.2.4.1-1 describes the aircraft performance modeling data defined.

Data	Description
<b>FAA Aircraft Type</b>	FAA 4-Letter ID found in flight plan data.
<b>Gross Wing Area</b>	Reference wing area
<b>Maximum Takeoff Weight</b>	Max takeoff weight
<b>Operating Weight Empty</b>	Operating empty weight
<b>Max Weight Flap Deflection Speeds</b>	Flap deflection speeds for each flap deflection at maximum aircraft weight
<b>Min Weight Flap Deflection Speeds</b>	Flap deflection speeds for each flap deflection at minimum aircraft weight
<b>Approach Speed Slope</b>	Slope produced from graphing approach speed versus weight for the normal approach flap setting.
<b>Max Approach Weight Speed Slope</b>	Approach speed for the aircraft's maximum weight with a normal flap setting
<b>Engine Type</b>	JET, TURBOPROP or PROP
<b>Drag Model</b>	Defines the (airframe) drag model for this aircraft model
<b>Thrust Model</b>	Defines the (engine) thrust model for this aircraft model
<b>Drag Scale Factor</b>	A scaling multiplier used to scale another airframe's drag model for use with this aircraft model.
<b>Thrust Scale Factor</b>	A scaling multiplier used to scale another engine's thrust model for use with this aircraft model.
<b>Maximum Mach Number</b>	Maximum allowable Mach number.
<b>Maximum Cruise Mach Number</b>	Maximum allowable Mach number in cruise.
<b>Minimum CAS</b>	Minimum allowable CAS.
<b>Maximum CAS</b>	Maximum allowable CAS.
<b>Minimum Cruise CAS</b>	Minimum allowable CAS in cruise.
<b>Maximum Cruise CAS</b>	Maximum allowable CAS in cruise.
<b>Typical Descent Weight</b>	Default descent weight for this aircraft.
<b>Default Descent CAS</b>	Default descent CAS for this aircraft.
<b>Default Ascent CAS</b>	Default climb CAS for this aircraft.

**Table 4.2.4.1-1 CTAS En Route TP Aircraft Specific Performance Model Data**

Not all aircraft models have detailed airframe (drag) and engine (thrust) model data available. For these, a suitable base drag and thrust model is chosen and a value for the drag and thrust scale factors must be determined to give acceptable aircraft modeling performance.

Table 4.2.4.1-2 describes the airframe drag modeling data used by the drag models within the CTAS En Route TP.

Data	Description
<b>Clean Drag Polars</b>	Provides the drag coefficient ( $C_D$ ) for the aircraft with no slats or flaps deflected. $C_D$ varies as a function of Mach number and lift coefficient ( $C_L$ ).
<b>Flap Extended Drag Polars</b>	Provides the drag coefficient ( $C_D$ ) for the aircraft with flaps deflected. For each flap deflection angle, $C_D$ varies as a function of lift coefficient ( $C_L$ ).
<b>Landing Gear Drag Coefficient Increment</b>	Provides the drag coefficient ( $C_D$ ) for the additional drag added (to the appropriate flap drag polar) when the landing gear are dropped. For each flap deflection angle, $C_D$ varies as a function of lift coefficient ( $C_L$ ).
<b>Landing Gear Multiplier (LGM)</b>	Provides a scaling factor to the landing gear drag coefficient ( $C_D$ ) to cover increased drag at higher speeds. This multiplier varies as a function of Mach number.
<b>Speed Brake Drag Coefficient Increment</b>	Provides the drag coefficient ( $C_D$ ) for the additional drag added when the speed brakes are deployed. This $C_D$ varies as a function of Mach number.

**Table 4.2.4.1-2 CTAS En Route TP Airframe Drag Model Data**

The total drag coefficient on the aircraft is then:

$$C_{D,\text{total}} = C_{D,\text{base}} + (LGM \cdot C_{D,\text{gear}}) + C_{D,\text{speed brake}}$$

where the base CD is either from the clean or flap extended drag polar, whichever is appropriate.

The airframe drag models currently available within CTAS are:

- Airbus: A320-200, A321, A340-343
- Boeing: 727-200, 737-200, 737-300, 737-400, 737-500, 737-700, 737-800, 757-200 (with Pratt & Whitney engines), 757-200 (with Rolls-Royce engines), 767-200ER, 767-300, Boeing 777-200A, 777-200B
- McDonnell-Douglas: DC-9, MD-80, DC10
- Canadair LTD: CRJ-100/200/400
- Gulfstream Aerospace: Gulfstream IV
- Cessna: 172
- Beechcraft: Super Kingair 200
- Embraer: Bandeirante EMB-110, Brasilia EMB-120
- Fokker BV: 100

Tables 4.2.4.1-3 and 4.2.4.1-4 describe the engine thrust modeling data used by the thrust models within the CTAS En Route TP for Jets and Turboprops, respectively. For Jets<sup>15</sup>, not all data is available for all models. Specifically, models include N1 data, EGT data, EPR data or some combination of these.

Data	Description
<b>Idle Thrust</b>	Provides the thrust when the throttles are set at idle. Given as a function of altitude and Mach number (and sometimes temperature).
<b>Idle Fuel Flow</b>	Provides the fuel consumption when the throttles are set at idle. Given as a function of altitude and Mach number (and sometimes temperature).
<b>Corrected Fuel Flow</b>	Provides the fuel consumption at a given thrust value. Given as a function of Mach number and corrected thrust (and sometimes altitude).
<b>Max Climb N1</b>	Provides the maximum climb rotor speed (N1) as a function of ambient pressure.
<b>Max Cruise N1</b>	Provides the maximum cruise rotor speed (N1) as a function of ambient pressure.
<b>Corrected Thrust (N1)</b>	Provides the corrected thrust as a function of Mach number and corrected rotor speed (N1).
<b>Max Cruise Thrust (N1 direct)</b>	Provides the corrected max cruise thrust as a function of Mach number, temperature and altitude.
<b>Max Climb Thrust (N1 direct)</b>	Provides the corrected max climb thrust as a function of Mach number, temperature and altitude.
<b>Max Climb EGT</b>	Provides the maximum climb exhaust gas temperature (EGT) as a function of ambient pressure.
<b>Max Cruise EGT</b>	Provides the maximum cruise exhaust gas temperature (EGT) as a function of ambient pressure.
<b>Corrected Thrust (EGT)</b>	Provides the corrected thrust as a function of Mach number and corrected exhaust gas temperature (EGT).
<b>Max Climb EPR</b>	Provides the maximum climb engine pressure ratio (EPR) as a function of total temperature and altitude.
<b>Climb EPR Bleed</b>	Provides a correction to the climb engine

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<sup>15</sup> NOTE: Some turboprop and propeller models had been converted to the equivalent of an EPR-based Jet model for implementation convenience.

<b>Max Cruise EPR</b>	pressure ratio (EPR) as a function of altitude.
<b>Cruise EPR Bleed</b>	Provides the maximum cruise engine pressure ratio (EPR) as a function of total temperature and altitude.
<b>Corrected Thrust (EPR)</b>	Provides a correction to the cruise engine pressure ratio (EPR) as a function of altitude.
<b>Corrected Fuel Flow (EPR)</b>	Provides the corrected thrust as a function of Mach number and engine pressure ratio (EPR).
<b>Corrected Thrust (Scrubbing Drag)</b>	Provides the fuel consumption as a function of Mach number and engine pressure ratio (EPR).
<b>Cruise/Climb Temperature Limit</b>	Provides the corrected thrust due to scrubbing drag on the core tail cone. Given as a function of Mach number and corrected drag.
	Given as a function of ambient pressure.

**Table 4.2.4.1-3 CTAS En Route TP Jet Engine Thrust Model Data**

Data	Description
<b>Idle Thrust</b>	Provides the thrust when the throttles are set at idle. Given as a function of altitude and true airspeed.
<b>Max Climb Thrust</b>	Provides the thrust for when the throttles are set at max climb. Given as a function of altitude, temperature, and true airspeed.
<b>Max Cruise Thrust</b>	Provides the thrust for when the throttles are set at max cruise. Given as a function of altitude, temperature, and true airspeed.

**Table 4.2.4.1-4 CTAS En Route TP Turboprop Engine Thrust Model Data**

The engine thrust models currently available within CTAS are:

- General Electric: CF6-6D (N1 & EGT), CF6-80C2B1F (N1 Direct), CF6-80C2B2 (N1 Direct), CF6-80C2B6 (N1 Direct), CF6-80A2 (N1 Direct), CFM56-3B-2 (N1 Direct), CFM56-3 (N1 Direct), CFM56-7B20 (N1 Direct), CFM56-7B22 (N1 Direct), CFM56-7B24 (N1 Direct), CFM56-7B26 (N1 Direct), GE90-76B/85B (N1 Direct), GE90-90B (N1 Direct)
- Pratt & Whitney: JT8D-217 (EPR), JT8D-15 (EPR), JT8D-17 (N1 Direct), JT8D-07 (EPR), JT8D-9 (N1 Direct), JT9D-7R4D (N1 Direct), PT6A-42 (EPR), PW118 (Turboprop), PT6A-34 (Turboprop), PW2037 (N1 Direct), PW2040 (N1 Direct), PW4056 (N1 Direct), PW4074 (N1 Direct), PW4077/84 (N1 Direct), PW4050 (III) (N1 Direct), PW4052 (III) (N1 Direct), PW4056 (III) (N1 Direct), PW4056 (III)-2 (N1 Direct), PW4090 (N1 Direct)
- Rolls-Royce: TRENT884/877 (N1 Direct), TRENT892 (N1 Direct), RB211-524G/H2 (N1 Direct), RB211-524H (N1 Direct), RB211-535E4-B (N1 Direct), RB211-535C (N1 Direct)

- Honeywell: HW\_TPE331-10T (Turboprop)
- Avco: O-320-H2AD (EPR)

#### *4.2.4.1. Thrust “Correction” For Climb Profiles*

Given a Climb CAS and Climb Mach, the CTAS TP confirms that its engine model for that aircraft has sufficient thrust to reach the desired cruise altitude. If there is insufficient thrust to reach the cruise altitude, the aircraft model’s thrust scale factor is increased to enable a minimum energy rate of 0.01g to reach the cruise altitude.

The energy rate at the cruise altitude is estimated from:

$$\dot{e} = \frac{(T_{TOC} - D_{TOC})}{Weight}$$

where

$T_{TOC}$  = the thrust at the top of climb (using the aircraft model’s thrust data at initial condition position, the cruise altitude, the Climb Mach, and maximum Climb thrust)

$D_{TOC}$  = the drag at the top of climb (using the aircraft model’s drag data at initial condition position, the cruise altitude, the Climb Mach and maximum Climb thrust)

Weight = 90% of the aircraft model’s maximum takeoff weight

If the estimated energy rate is less than 0.01g, the aircraft model’s thrust scale factor is increased to equal 0.01g at the top of climb.

#### *4.2.4.2. Adaptive Thrust*

When requested through an input (Adaptive Thrust Modeling), the adaptive thrust processing modifies the aircraft model’s thrust so the predicted climb rate asymptotically approaches an observed climb rate.

Processing starts by predicting the current track’s altitude from the previous track altitude and the previous track’s predicted altitude rate<sup>16</sup> (both input to the TP). The current radar track’s altitude ( $h_{actual}$ ) is compared to this predicted altitude ( $h_{predicted}$ ) to determine the deficiency in the previous track’s predicted altitude rate. This deficiency is turned into a required increase in thrust by the following equation:

$$\Delta Thrust = \frac{h_{actual} - h_{predicted}}{V_G * \beta * W}$$

where

$V_G$  = current track ground speed

$\beta$  = kinetic energy rate scale factor (set to 0.003)

$W$  = 90% of the aircraft model’s maximum takeoff weight

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<sup>16</sup> Assumed that this rate is calculated from the previous trajectory predicted by the TP.

The thrust scale factor for the aircraft model is modified so that the current thrust equals the aircraft model's unmodified thrust plus the required ΔThrust.

#### 4.2.5. Computed Trajectory

The final trajectory elements returned by the Trajectory Engine of the CTAS En Route TP are defined in Tables 4.2.5-1 and 4.2.5-2. Table 4.2.5-1 presents the time oriented data that is returned whenever a request to the CTAS En Route TP is made. Table 4.2.5-2 presents the specific trajectory data output that can optionally be returned.

Data	Description
<b>ID</b>	Used by the Client Application to correlate the trajectory response with a trajectory request.
<b>Advisory Time</b>	The estimated time of arrival at the last point in the trajectory. For meet-time scenarios, this is the ETA at the metering fix. For non-meet-time cases, this is the NOMINAL trajectory time.
<b>Fast Time</b>	The estimated time of arrival of the FAST trajectory at the last point in the trajectory.
<b>Slow Time</b>	The estimated time of arrival of the SLOW trajectory at the last point in the trajectory.
<b>Standard Time</b>	The estimated time of arrival of the trajectory using company-preferred speed profiles at the last point in the trajectory.
<b>Error Flag</b>	Identifies a failed trajectory or a trajectory warning.
<b>Error Type &amp; Message</b>	Describes situation that caused a trajectory failure.

**Table 4.2.5-1 CTAS En Route TP Trajectory Engine Estimated Time of Arrival Output Format**

Data	Description
<b>Identifier</b>	Used by the Client Application to correlate the trajectory response with a trajectory request.
<b>Contains Ascent</b>	Boolean to describe whether a Climb segment was modeled.
<b>Waypoint Capture Mode</b>	Boolean alerting to Waypoint Capture mode modeled.
<b>Final Waypoint Reference</b>	Indicates what is the final waypoint of the trajectory.
<b>Time Reference</b>	Initial track time (used as base time for all other values)
<b>Number of Integration Steps</b>	Number of predicted future states (plus one for initial condition)
<b>Number of Turn Endpoints</b>	Every turn consists of two endpoints, the

		start of the turn and the completion of the turn.
<b>Top of Ascent Time</b>		Estimated time of arrival (delta from base time) at the Top of Climb. (4.2.2.2.1)
<b>Overshoot Turn Waypoint Index</b>		Identifies a turn waypoint requiring an overshoot of the next turn waypoint.
<b>Cruise Altitude Change Position</b>		X/Y location of the End of Step for a Descent Step Change Mode (4.2.2.2.4)
<b>Initial CAS</b>		Initial ground speed converted to calibrated airspeed at initial altitude.
<b>Initial TAS</b>		Initial ground speed converted to true airspeed at initial altitude.
<b>Initial Mach</b>		Initial ground speed converted to Mach at initial altitude.
<b>Distance to TOD</b>		Distance from initial condition to predicted TOD point.
<b>Final altitude and CAS</b>		Altitude and CAS at final waypoint
<b>Max Cruise Mach</b>		Max cruise Mach from aircraft model.
<b>Max Cruise CAS</b>		Max cruise CAS from aircraft model.
<b>Max Descent CAS</b>		Max descent CAS from aircraft model.
<b>Min Cruise Mach</b>		Min cruise Mach from aircraft model.
<b>Min Cruise CAS</b>		Min cruise CAS from aircraft model.
<b>Min Descent CAS</b>		Min descent CAS from aircraft model.
<b>For Each Turn Endpoint</b>		
	<b>Start Turn</b>	Is the endpoint a start of a turn.
	<b>Horizontal Path Distance</b>	Along path distance (s)
	<b>Delta Path Distance</b>	Distance along path from last turn endpoint
	<b>Course Angle</b>	Predicted course angle
	<b>Position</b>	In x/y
	<b>Waypoint Position</b>	X/Y location of the waypoint that created the turn endpoint.
	<b>Heading</b>	Predicted magnetic heading
	<b>Turn Angle</b>	Angle turned through at this point (positive means right)
	<b>Turn Radius</b>	If turning
	<b>Bank Angle</b>	If turning
	<b>Turn center</b>	x/y position
<b>For Each Vertical Integration Step</b>		
	<b>Time</b>	Predicted time, seconds from initial condition time
	<b>Horizontal Path Distance</b>	Predicted along path distance (s)
	<b>Altitude</b>	Predicted geometric altitude
	<b>Ground Speed</b>	Predicted ground speed
	<b>CAS</b>	Predicted calibrated airspeed
	<b>TAS</b>	Predicted true airspeed
	<b>Mach</b>	Predicted Mach number
	<b>Vertical Speed</b>	Predicted vertical speed
	<b>Energy Rate</b>	Predicted energy rate
<b>Air Heading After First Turn</b>		Used for turn advisories with Waypoint

<b>Course Before First Turn</b>	<b>Capture mode.</b>
<b>Course After First Turn</b>	<b>Magnetic ground track before turn</b>
<b>First Turn Center Position</b>	<b>Magnetic ground after before turn</b>
<b>TOD Position and DME distance</b>	<b>In x/y</b>
<b>TOA Position and DME distance</b>	<b>Location of TOD in both x/y and as a distance from the input reference waypoint</b>
<b>Waypoint Capture Air Heading</b>	<b>Location of TOA in both x/y and as a distance from the input reference waypoint</b>
	<b>Used with Path Stretch mode to advise a turn to capture the capture waypoint after input delay.</b>

**Table 4.2.5-2 CTAS En Route TP Trajectory Engine Trajectory Output Format**

### **4.3. Trajectory Update Process**

#### **4.3.1. Iterative Intent Processes Supported**

##### ***4.3.1.1. Relaxed Meter Fix***

This processing occurs when given the aircraft is unable to descend at a fast enough altitude rate to achieve the crossing restriction altitude at the crossing restriction location (e.g., the metering fix). This can occur when a Descent Only Profile (i.e., a Fixed TOD Descent Sub-mode) fails or when a Cruise Then Descent Profile fails (a Fixed TOD Descent Sub-mode is attempted first and must also fail before relaxing the meter fix).

In this case, the crossing restriction altitude constraint is removed (i.e., “relaxed”) and the CTAS TP predicts the lowest achievable altitude at the crossing restriction location.

##### ***4.3.1.2. Relaxed Cruise Altitude***

When a “Climb, Cruise, Then Descent” Profile is necessary, it is possible that based on the aircraft’s initial condition, it is unable to reach the assigned cruise altitude before needing to initiate the descent. In this case, the cruise altitude is lowered (through an iterative process of building the climb and descent segments) to a value that enables a 20 nmi cruise segment before initiating the descent.

In the extreme case, the initial altitude is maintained (i.e., no climb) until capturing the descent profile.

##### ***4.3.1.3. Relaxed Cruise Speed***

During a “Cruise Only” Profile, if acceleration to an input Cruise Speed is unachievable, then the fastest Cruise Speed achievable is maintained during the Cruise Mode.

##### ***4.3.1.4. Relaxed Step Altitude***

If there is a failure in building the Descent Mode up to the new cruise altitude, the cruise altitude is removed and a descent up to the initial condition altitude is attempted.

### 4.3.2. Update Intent Modeling

#### *4.3.2.1. Relaxed Meter Fix Modeling*

The relaxed meter fix is a variation of a Fixed TOD Descent Mode. Specifically, the Capture Bottom of Descent Sub-Mode is used with:

- engine control set to Idle Thrust
- the descent CAS is set equal to the initial CAS
- a constant flight path angle is chosen to capture the path distance at the crossing condition (i.e., metering fix)

No changes to preparation process outputs other than the procedures described above are required.

#### *4.3.2.2. Relaxed Cruise Altitude Modeling*

The cruise altitude is lowered through an iterative process. Repeated calls to the Trajectory Engine are done with the cruise altitude modified to the highest reachable climb altitude prior to the Top-Of-Descent point (calculated first for each call using the current cruise altitude) by the previous call to the Trajectory Engine. The process stops when at least a 20 nmi cruise segment has been achieved.

No changes to preparation process outputs other than the cruise altitude are required.

#### *4.3.2.3. Relaxed Cruise Speed Modeling*

The maximum cruise speed attained during the previous integration attempt is entered as an input Cruise Speed value and the Trajectory Engine processing redone.

No changes to preparation process outputs other than the cruise speed are required.

#### *4.3.2.4. Relaxed Step Altitude Modeling*

The new cruise altitude is removed and the Trajectory Engine processing is redone. If this fails, the trajectory fails.

No changes to preparation process outputs other than the removal of the new cruise altitude are required.

### 4.3.3. Trajectory Refresh Monitoring

The CTAS En Route TP uses cyclic refreshing. An aircraft's predicted trajectory is refreshed with every new radar track received. This is equivalent to a 12 second cyclic refresh rate. Non-active (i.e., no track received) aircraft are not refreshed.

## **4.4. TP Export Process**

### **4.4.1. Client Format Service**

The computed trajectory from the Trajectory Engine (see Section 4.2.5) is formatted for use by the CTAS Client Applications. The lateral and vertical data from the Trajectory Engine are used to interpolate a time step every 10 seconds, starting at the initial condition. Table 4.4.1-1 presents the data contained in each time step for the final trajectory.

<b>Data</b>	<b>Description</b>
<b>Time</b>	<b>Predicted time</b>
<b>X/Y</b>	<b>Predicted position</b>
<b>Path Distance</b>	<b>Predicted along path distance</b>
<b>Vertical Speed</b>	<b>Predicted vertical speed</b>
<b>Altitude</b>	<b>Predicted altitude</b>
<b>Groundspeed</b>	<b>Predicted groundspeed</b>
<b>True Airspeed</b>	<b>Predicted true airspeed</b>
<b>Calibrated Airspeed</b>	<b>Predicted CAS</b>
<b>Mach</b>	<b>Predicted Mach number</b>
<b>Ground Course</b>	<b>Predicted true course</b>
<b>Heading</b>	<b>Predicted true heading (air referenced)</b>

**Table 4.4.1-1: Client Trajectory Format**

### **4.4.2. Client Processing Services**

#### **4.4.2.1. FRD Representation of Top-of-Descent**

In support of Descent Speed Advisory clearances, the predicted top-of-descent (TOD) must be returned in a format that is able to be delivered as a verbal clearance to a pilot. A reference waypoint (input to the CTAS En Route TP) is used as the foundation for the generation of a fix-radial-distance (FRD) representation for the TOD location. The resultant representation describes the variable (i.e., not a published value) location of the TOD as a set distance along a specified radial from the input (published) reference waypoint.

## **5. NON-FUNCTIONAL REQUIREMENTS**

The CTAS En Route TP is an element of a research system (CTAS) designed to support concept feasibility experiments. As such, there are no “specified” performance requirements for the CTAS En Route TP. There are, however, implied requirements derived from areas where the performance of the CTAS En Route TP can impact concept feasibility and where the CTAS En Route TP’s performance needs to be maximized, to the extent possible.

In lieu of specific performance requirements (which do not currently exist), the descriptions below focus on CTAS functionality affected by the stated TP performance and implied requirements.

### **5.1. Trajectory Prediction Accuracy Requirements & Capabilities**

Since the main goal of CTAS is to provide maneuver clearance and flow constraint advisories to controllers and traffic managers, all of the CTAS functionality is directly impacted by the prediction accuracy of the CTAS En Route TP. Specifically, if the prediction accuracy is not sufficient for a particular functionality, that functionality’s resultant advisories will not be effective in accomplishing its conceptual objectives. This can result in concept infeasibility.

Since the requirements for CTAS functionality are constantly being refined, the CTAS En Route TP prediction accuracy requirements are also in flux and the implied requirement is to maintain as high a level of prediction accuracy as is reasonable (given resource constraints) to maintain sufficient functional performance.

#### **5.1.1. Longitudinal Trajectory Error**

Longitudinal errors, either expressed as a time error at a predicted location or as an along track spatial error at a predicted time, have a direct impact on all CTAS functionality, including:

- scheduling algorithms
- conflict detection algorithms (used for conflict probe, trial planning, and conflict resolution)
- meet-time algorithms
- descent management algorithms

#### **5.1.2. Lateral Trajectory Error**

Lateral errors, primarily expressed as a cross-track error at a predicted location or time, have a direct impact on conflict detection algorithms and a secondary impact on meet-time and descent management algorithms.

#### **5.1.3. Vertical Trajectory Error**

Vertical errors, primarily expressed as an altitude error at a predicted location or time, have a direct impact on conflict detection algorithms and a secondary impact on meet-time and descent management algorithms.

## **5.2. Computational Performance Requirements & Capabilities**

There are two primary implied computation requirements for the CTAS En Route TP:

- Be fast enough to achieve all required processing in the “required time allotted”
- Be fast enough to respond back to controller requests in a controller acceptable amount of time

Since CTAS does not break down its performance requirements into allotted times for its individual components (e.g., trajectory prediction, conflict detection, conflict resolution, etc.), the first requirement simply implies that the CTAS En Route TP should not be the bottleneck in completing the basic CTAS processing within its 12 second processing cycle.<sup>17</sup> As should be expected for a research system, the number of elements within the basic processing cycle can vary as new concept requirements are determined.

Concurrent with the basic processing cycle, the CTAS En Route TP must also not be the bottleneck in achieving an acceptable response time to off-cycle controller processing requests. Examples include processing flight plan amendments and trial plans. Again, the number and types of potential off-cycle processing varies as new research identifies additional requirements.

Historically, to deal with the variability in computational requirements for CTAS, if system (i.e., CTAS, not just the CTAS En Route TP) computation speed became an issue, the CTAS architecture was changed to extend the multi-process design to bring in more processors. For example, the old Planview Display (a single process) was turned into the modern PGUI-RA-PFS architecture (a minimum of three processes, but additional RA processes can be added as required) to eliminate processing bottlenecks.

## **5.3. Security Requirements & Capabilities**

CTAS is designed to run either in a NASA laboratory environment or within an ARTCC facility. These environments are sufficiently controlled that there are no additional security requirements for the CTAS En Route TP.

## **5.4. Quality Standards Requirements & Capabilities**

CTAS has a set of coding standards that apply to all CTAS processes, including the CTAS En Route TP:

- CTAS ‘C’ Coding Standards, Standard (ANSI) C Version 4.0
- Center TRACON Automation System, The C++ Coding Standard, Release 1.1
- Center TRACON Automation System, Java Coding Standards, Release 1.0

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<sup>17</sup> Basic CTAS processing includes refreshing all active aircraft trajectories, conflict probe, and conflict resolution advisories (if any). The basic processing cycle is initiated when a new set of radar tracks is received and needs to be completed before the next set of radar tracks arrive (approximately 12 seconds later).

There are no other quality standard requirements.

## 6. ACRONYMS

ARTCC	Air Route Traffic Control Center
AWIPS	Advanced Weather Interactive Processing System
BOD	Bottom of Descent
BOS	Begin of Step
CAS	Calibrated Airspeed
CM	Communications Manager
CTAS	Center-TRACON Automation System
D2	Direct-To DST
DME	Distance Measuring Equipment
DP	Dynamic Planner
DST	Decision Support Tool
DTA	Descent Transition Altitude
EDA	En Route Descent Advisor DST
EGT	Engine Gas Temperature
EOS	End of Step
EPR	Engine Pressure Ratio
FAA	Federal Aviation Administration
FRD	Fix Radial Distance
IAS	Indicated Airspeed
ISM	Input Source Manager
LGM	Landing Gear Multiplier
MCTA	M(ach)/CAS Transition Altitude
N1	Compressor Speed
PAR	Preferred Arrival Route
PDAR	Preferred Departure/Arrival Route
PDR	Preferred Departure Route
PFS	Profile Selector
RA	Route Analyzer
RUC	Rapid Update Cycle
SID	Standard instrument Departure
STAR	Standard Arrival Route
TFM	Traffic Flow Management
TGUI	Traffic Management Graphical User Interface
TMA	Traffic Management Advisor DST
TOA	Top of Ascent
TOC	Top of Climb
TOD	Top of descent
TP	Trajectory Predictor
TRACON	Terminal Radar Approach Control
TS	Trajectory Synthesizer
VFR	Visual Flight Rules

## **Appendix A: Host Computer Planar Projection**

**TBD** – Request made to Mike Paglione of the FAA technical Center for a good Host reference document.

## Appendix B: CTAS Track Filtering

### Data Sanity Checks

If the track data fails any of the following tests, additional tests are performed to determine whether the track should be dropped:

Check	Condition	Action
Groundspeed too large	Groundspeed > 1300.0 ft/sec	Current Groundspeed value set equal to previous value
Host track in coast mode	In coast mode and previous time < 0	N/A
No position update	Current position (x/y) equals previous position (x/y)	N/A
Negative x coordinate	x < 0	Current x value set equal to previous value
Negative y coordinate	y < 0	Current y value set equal to previous value
Invalid altitude data	Current altitude < 0 or > 60000 ft	N/A
No altitude data	Current altitude = 0	Current altitude value set equal to previous value

Additional tests: If the data fails any of these tests, the track is dropped.

Check	Condition
No valid previous data	Previous time <= 0
Previous data too old	Current time – previous time > 60
Tracks too close in time	Current time – previous time < 1
Position data not updated	Current position (x/y) equals previous position (x/y)

If data passes all of the sanity checks, then filters are applied.

### Filters

The following are the set of filters that can be applied to the various fields within the track data:

Ground Speed ( $V_G$ ) Filters:

### *Eliminate Spikes:*

$V_{G,current}$  is initially set to the input ground speed.

If there is no average ground speed available from previous data and:

$V_{G,current} < 50kts$  or  $V_{G,current} > 800kts$   
then  $V_{G,current}$  is replaced with the filed true airspeed.

If there is an average ground speed available from previous data and:

$V_{G,current} < 50kts$  or  $V_{G,current} > 800kts$   
then  $V_{G,current} = \text{previous average.}$

The acceleration from the last track hit to the current track hit ( $a$ ) is:

$$a = \frac{V_{G,current} - V_{G,previous}}{t_{current} - t_{previous}}$$

If  $a > 0.1*g$ , then:

$$V_{G,current} = V_{G,previous} + 0.1 * g * (t_{current} - t_{previous})$$

If  $a < -0.1*g$ , then:

$$V_{G,current} = V_{G,previous} - 0.1 * g * (t_{current} - t_{previous})$$

### *Handle “Cone of Silence”:*

**TBD**

### *Apply Filters:*

There are three filters that can be applied to the ground speed (depending on CTAS configuration):

1. Simple moving average filter
2. Low pass filter
3. Least squares filter

### Vertical Speed Filters:

#### *Calculate Raw Vertical Speed:*

“Raw” vertical speed is calculated from two successive tracks.

If no previous altitude or time, vertical speed = 0.

If previous altitude and time data:

$$\text{rawVerticalSpeed} = \frac{h_{current} - h_{previous}}{t_{current} - t_{previous}}$$

*Apply Filters:*

There are two filters that can be applied to the raw vertical speed (depending on CTAS configuration):

1. Simple moving average filter
2. Least squares filter

Course (Ground Track) Filters:

*Check Validity of Position Data:*

If first track data, assume valid.

The track position data is valid if:

- time between track updates exceeds length of regression window (`nominal_update_period*5`)
- estimated turn rate exceeds 10 degrees/second
- distance between current and previous positions exceeds  $2.5 * \Delta t * V_G$  or is less than  $0.4 * \Delta t * V_G$

If the position is invalid, use previous true course data.

If more than 3 consecutive bad position data, re-initialize the heading filter.

*Calculate Raw True Course:*

If first track, assume true course from current position to airport position.

If previous position data exists, calculate true course from previous position to current position.

*Apply Filters:*

There is one filter that can be applied to the raw true course (depending on CTAS configuration):

1. Least squares filter